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Application of Taguchi Experimental Design Method to Find an Optimum Composition of Mortar Mix Material with Silica Fume

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Abstract. Improving mortar performance and reducing cement consumption through the use of pozzolanic additives, such as silica fume, supports sustainable construction. Reducing cement usage is essential, given the significant contribution of cement production to global CO_2 emissions. This study aims to determine the optimum mortar mix composition using the Taguchi experimental design method. Four key factors—cement, sand, silica fume, and water—were tested at four levels using an L16(4^5) orthogonal array. Cube specimens (5 × 5 × 5 cm) were tested for compressive strength at 28 days. The optimum mix consisted of 71.99 g cement, 165 g sand, 15 g silica fume (20.836% of cement weight), and 37.25 g water, with a water-to-cement ratio (W/C) of 0.52, equivalent to a water-to-binder ratio (FAB) of 0.43, resulting in a compressive strength of 57.14 MPa. ANOVA results showed that water had the most significant influence (45.377%), followed by cement (15.027%), sand (11.260%), and silica fume (7.590%). The Taguchi method effectively identified the optimal combination with minimal trials. Confirmation tests showed results within the predicted confidence interval, validating the optimum mix. The optimized composition exceeded the strength requirements for Type M mortar (SNI 03-6882-2002), indicating its suitability for sustainable structural applications requiring high compressive strength.

Introduction

The continuous growth of infrastructure development has increased the demand for construction materials that exhibit high performance and support sustainability principles. One of the primary materials in construction is cement, which is extensively used in both concrete and mortar mixes. However, conventional cement production significantly contributes to carbon dioxide (CO_2) emissions. According to Chatham House, global cement production releases approximately 2.2 billion tons of CO_2 annually, accounting for around 8% of total global emissions. This production process has a major impact on global warming and climate change. Alternatives that can lessen the dependency on cement and enhance mortar performance are necessary to tackle this issue. One is the use of pozzolanic admixtures such as silica fume. Silica fume is a material made from the production of silicon or ferrosilicon, known for its very small particles and high silica levels, which makes it very effective in chemical reactions that enhance mortar. Several studies have shown that the addition of silica fume can increase compressive strength, reduce porosity, and improve the durability of mortar in aggressive environments [1, 2, 3]

According to [1], silica fume plays a significant role in enhancing the microstructure of mortar by filling voids that could weaken the material, thus increasing overall strength. It also improves pozzolanic reactions, contributing to stronger bonds between cement particles [1]. Adding 7.5% silica fume can create stronger concrete, reaching a maximum compressive strength of 336 kg/cm², which is better than the 316 kg/cm² from using 20% fly ash [2]. This evidence indicates that silica fume is more effective even at lower dosages. In another study, replacing 0–10% of cement with silica fume allowed 0.5 kg of silica fume to replace 1.5–2 kg of cement without compromising compressive strength [4]. Also, silica fume contains more SiO_2 (85–97%) than fly ash (61.32%), which leads to better pozzolanic reactivity and creates C-S-H gel that improves the strength and density of mortar [5].

However, to date, there is no universally accepted mix composition for silica fume-based mortar that guarantees optimum performance, as local material characteristics and mixing conditions can significantly affect the final properties. Therefore, a scientific approach is needed to systematically and efficiently determine the optimal mix composition. One method that can be used for this purpose is the Taguchi experimental design method, a Design of Experiments (DoE) approach that is effective in identifying dominant factors and optimal levels with a minimal number of experiments. Based on the principles of robust design, this method enables efficient experimentation in terms of time, cost, and resources [6].

The Taguchi method is also considered appropriate because it can handle research problems involving many factors and levels simultaneously. By employing orthogonal arrays, Taguchi reduces the number of experimental combinations that would otherwise be very large, without diminishing the ability to analyze the main effects of each factor. In addition, the Signal-to-Noise (S/N) ratio analysis helps evaluate the stability of responses against variations in factors, ensuring that the results are not only optimal but also robust under varying conditions [7]. Therefore, this method is highly suitable for determining the optimum composition of silica fume-based mortar, which is influenced by multiple interacting variables, while still saving time, cost, and material resources.

This study applies the Taguchi method to determine the optimum mortar composition using silica fume in the range of approximately ±5–20% of the cement weight. The research focuses on four main factors: cement, sand, silica fume, and water, each with four variation levels, arranged using an $L16(4^5)$ orthogonal array. Mortar specimens were shaped into cubes (50 × 50 × 50 mm) and tested for compressive strength at 28 days. The results of this study are expected to contribute to the development of environmentally friendly, high-performance mortar.

Method

Materials and Equipment. The main materials used in this study were Gresik brand Portland Composite Cement (PCC), local sand from East Lombok Regency, silica fume from PT Sika Indonesia, and clean water that met the Indonesian National Standard (SNI) for mixing mortar. Silica fume replaced about 5–20% of the cement by weight. No superplasticizer was added to the mortar mix. The key physical and chemical properties of the main materials are summarized in **Table 1**. The equipment used consisted of a digital scale, 50 × 50 × 50 mm cube molds, a mortar mixer, a vibrating table, and a Compression Testing Machine (CTM) with a capacity of 2000 kN for compressive strength testing.

Table 1. Physical and Chemical Properties of Materials

Material	Physical Properties	Chemical Properties
Cement (PCC)	Fineness, no lumps, complies with SNI standard	Mainly CaO, SiO_2, Al_2O_3 (typical PCC composition)
Sand	Fineness modulus ≈ 3.52, specific gravity ≈ 2.61, water absorption 2.08%	–
Silica fume	Particle size 0.1–1 µm,	SiO_2 ≈ 97,3% (dominant), minor oxides (K_2O, Al_2O_3, CaO, SO_3, Fe_2O_3, etc.)

Experimental Design. The experimental design in this study employed a Taguchi $L16(4^5)$ orthogonal array to determine the optimum combination of four main factors: cement (A), sand (B), silica fume (C), and water (D). Each factor was varied at four levels, as shown in **Table 2**. The selection of the $L16(4^5)$ matrix was based on consideration of the degrees of freedom (DOF). The total DOF for four factors, each with four levels, is 12 [(4 – 1) × 4 = 12], meaning that the L16 matrix, which has 15

DOF (16 – 1), is sufficient to represent the experimental variables as well as the residual error without causing a shortage in degrees of freedom. The detailed experimental design is presented in **Table 3**.

Table 2. Factor Level Values

Control Factor	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Cement (A)	10%	15%	20%	25%
Sand (B)	35%	45%	50%	55%
Silica fume (C)	5%	10%	15%	20%
Water (D)	0.35	0.40	0.45	0.50

In **Table 2**, the percentages of cement and sand are expressed relative to the total mortar mix weight, while the percentage of silica fume represents the proportion of cement replacement, calculated as 5–20% of cement weight. The percentage of water is expressed relative to the total binder weight (cement + silica fume). The factor levels shown in **Table 2** were selected based on standards, common practice, and previous studies. For cement and sand, the ratios were selected based on common practice and the work of Jauhar et al. [1], representing a range between 1:3.5 and 1:2.2. The silica fume content (5–20% by cement weight) was determined with reference to several studies [1, 8, 9], which indicated an optimum range of 10–15% with an increasing trend up to 20%. The water-to-cement ratio levels (0.35–0.50) were selected based on findings from Nugroho [10] and Subrianto [11], where 0.35 was found to provide optimum compressive strength, while values above 0.50 reduced strength due to excessive porosity.

Mortar Preparation and Compressive Strength Testing. The procedure and specifications for preparing mortar samples in this study refer to the guidelines outlined in the reference [12]. All materials were weighed according to the specified composition for each treatment, then mixed using a mortar mixer until a homogeneous mixture was obtained. The fresh mortar was placed into 50 × 50 × 50 mm cube molds in three layers, with each layer compacted using a tamping rod by applying 32 blows per layer. After 24 hours of curing, the specimens were demolded and immersed in clean water until the testing age of 28 days [6, 7]. The compressive strength test was carried out using a Compression Testing Machine (CTM) in accordance with the standard procedure [13]. Three specimens were produced for each treatment combination, and the average compressive strength value was used for analysis.

Table 3. Orthogonal Matrix L16(4^5)

Orthogonal Matrix L16(4^5)					**Mix Composition**							
Exp	**Factor**				**Factor (gram)**				**Factor (%)**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
1	1	1	1	1	61.01	213.52	3.05	22.42	20.34%	71.17%	1.02%	7.47%
1	1	1	1	1	61.01	213.52	3.05	22.42	20.34%	71.17%	1.02%	7.47%
2	1	2	2	2	61.01	198.24	6.61	29.07	20.69%	67.22%	2.24%	9.86%
3	1	3	3	3	61.01	179.96	10.80	37.25	21.11%	62.27%	3.74%	12.89%
4	1	4	4	4	61.01	165.00	15.00	45.00	21.33%	57.69%	5.24%	15.73%
5	2	1	2	3	66.08	213.52	6.61	37.25	20.43%	66.01%	2.04%	11.52%
6	2	2	1	4	66.08	198.24	3.05	45.00	21.15%	63.46%	0.98%	14.41%
7	2	3	4	1	66.08	179.96	15.00	22.42	23.31%	63.49%	5.29%	7.91%
8	2	4	3	2	66.08	165.00	10.80	29.07	24.39%	60.90%	3.99%	10.73%
9	3	1	3	4	71.99	213.52	10.80	45.00	21.09%	62.56%	3.16%	13.18%
10	3	2	4	3	71.99	198.24	15.00	37.25	22.32%	61.47%	4.65%	11.55%
11	3	3	1	2	71.99	179.96	3.05	29.07	25.34%	63.35%	1.07%	10.23%
12	3	4	2	1	71.99	165.00	6.61	22.42	27.06%	62.03%	2.48%	8.43%
13	4	1	4	2	75.00	213.52	15.00	29.07	22.55%	64.20%	4.51%	8.74%
14	4	2	3	1	75.00	198.24	10.80	22.42	24.47%	64.69%	3.52%	7.32%
15	4	3	2	4	75.00	179.96	6.61	45.00	24.46%	58.70%	2.16%	14.68%
16	4	4	1	3	75.00	165.00	3.05	37.25	26.76%	58.86%	1.09%	13.29%

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Description:
A= Cement, B = Sand, C = *Silica Fume,* D = Water

Results and Discussion

Mortar Compressive Strength. The test results show that the compressive strength of mortar varies for each mix combination. The average compressive strength values from all 16 combinations are presented in **Table 4.**

Table 4. Mortar Compressive Strength Test Results

Experiment	Cross-Sectional Area (mm²)			Maximum Load (N)			Compressive Strength (MPa)		
	I	II	III	I	II	III	I	II	III
1	2785.20	2633.69	2665.90	30000	31000	31000	10.771	11.771	11.628
2	2726.56	2722.18	2497.57	56000	58000	57000	20.539	21.306	22.822
3	2534.91	2526.88	2737.15	85000	82000	91000	33.532	32.451	33.246
4	2579.36	2675.74	2658.40	69000	71000	67000	26.751	26.535	25.203
5	2686.83	2609.09	2630.53	76000	76000	81000	28.286	29.129	30.792
6	2546.67	2590.55	2570.33	59000	61000	62000	23.168	23.547	24.121
7	2562.13	2475.24	2500.81	44000	44000	46000	17.173	17.776	18.394
8	2453.59	2628.06	2639.26	145000	141000	145000	59.097	53.652	54.940
9	2554.94	2561.62	2552.03	76000	75000	78000	29.746	29.278	30.564
10	2751.27	2588.91	2660.14	145000	153000	132000	52.703	59.098	49.622
11	2717.35	2785.73	2636.82	86000	81000	81000	31.648	29.077	30.719
12	2536.77	2671.16	2532.32	70000	75000	79000	27.594	28.078	31.197
13	2705.54	2564.37	2713.80	104000	104000	104000	38.440	40.556	38.323
14	2552.47	2708.68	2776.88	39000	38000	42000	15.279	14.029	15.125
15	2469.75	2461.08	2513.47	87000	87000	87000	35.226	35.350	34.613
16	2544.58	2635.92	2725.90	101000	102000	107000	39.692	38.696	39.253

Description: I = Sample 1, II = Sample 2, III = Sample 3

Analysis of the Mean Compressive Strength. An analysis of the mean compressive strength values was conducted to determine the effect of each factor on the experimental results. **Table 5** presents the average compressive strength obtained from each mix combination, based on the results of three specimens per experiment. Meanwhile, **Table 6** shows the influence range of each factor, calculated from the difference between the highest and lowest average values at each level.

Table 5. Average (Mean) Compressive Strength of Mortar

Orthogonal Matrix L16(4)⁵					Compressive Strength (MPa)			Total	Mean
Experiment	Factor								
	Cement	Sand	SF	Water	I	II	III		
1	1	1	1	1	10.771	11.771	11.628	34.170	11.390
2	1	2	2	2	20.539	21.306	22.822	64.667	21.556
3	1	3	3	3	33.532	32.451	33.246	99.229	33.076
4	1	4	4	4	26.751	26.535	25.203	78.489	26.163
5	2	1	2	3	28.286	29.129	30.792	88.207	29.402
6	2	2	1	4	23.168	23.547	24.121	70.836	23.612
7	2	3	4	1	17.173	17.776	18.394	53.343	17.781
8	2	4	3	2	59.097	53.652	54.940	167.688	55.896
9	3	1	3	4	29.746	29.278	30.564	89.589	29.863
10	3	2	4	3	52.703	59.098	49.622	161.423	53.808
11	3	3	1	2	31.648	29.077	30.719	91.444	30.481
12	3	4	2	1	27.594	28.078	31.197	86.869	28.956
13	4	1	4	2	38.440	40.556	38.323	117.318	39.106
14	4	2	3	1	15.279	14.029	15.125	44.433	14.811

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Experiment	Orthogonal Matrix L16(4)[5] Factor: Cement	Sand	SF	Water	Compressive Strength (MPa) I	II	III	Total	Mean
15	4	3	2	4	35.226	35.350	34.613	105.190	35.063
16	4	4	1	3	39.692	38.696	39.253	117.642	39.214
				Mean					30.636

Description: I = Sample 1, II = Sample 2, III = Sample 3

Table 6. Mean Response Values at Each Factor Level

Level	Cement	Sand	SF	Water
1	23.046	27.440	26.174	18.235
2	31.673	28.447	28.744	36.760
3	35.777	29.101	33.412	38.875
4	32.049	37.557	34.214	28.675
Range	12.731	10.117	8.040	20.640
Ranking	2	3	4	1

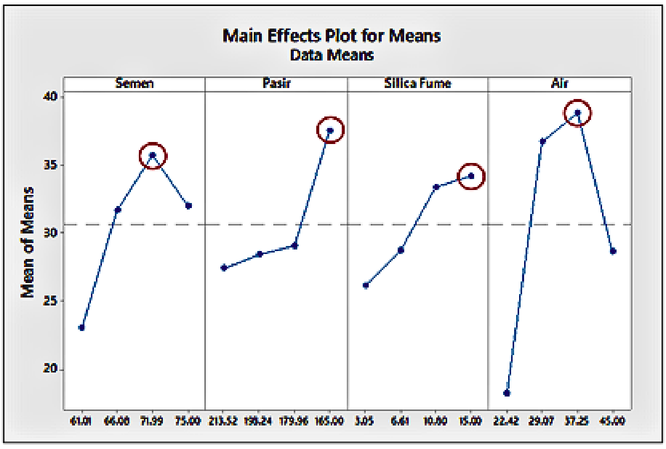

Fig. 1. *Main Effect Plot for Mean*

Fig. 1 shows how to find the best level for each factor based on the idea that higher values are better, meaning that stronger compressive strength leads to better mortar performance. For the cement factor, the highest average value is found at level 3, while for sand, the optimum level is achieved at level 4. For silica fume, level 4 yields the highest mean value, while level 3 yields the maximum value for water. Meanwhile, based on **Table 6**, it is evident that the water factor has the greatest influence on mortar compressive strength, as it exhibits the highest range between levels. This range reflects how much the average compressive strength changes due to variations in the factor levels. The greater the range, the more significant the effect of that factor on mortar strength. This data suggests that water is a highly sensitive variable, as it directly affects the water-cement ratio (W/C) in the mixture. Therefore, the ranking presented in **Table 6** is used to identify the most influential factors in the mortar mixing process based on their average compressive strength response.

Analysis of the Signal-to-Noise (S/N) Ratio. In addition to the mean value, analysis of the Signal-to-Noise (S/N) Ratio was conducted to evaluate the stability of the mortar compressive strength results. The response characteristic used was "larger-the-better," as higher and more consistent compressive strength values indicate better mortar performance. The S/N ratio was calculated for each combination in the experimental design, and the results were used to determine the optimum level for each factor. The average S/N ratio for each factor level is presented in **Table 7**.

Table 7. Signal-to-Noise (S/N) Ratio Values for Mortar Compressive Strength

Experiment	Orthogonal Matrix L16(4)[5] Factor: Cement	Sand	SF	Water	Compressive Strength (MPa) I	II	III	S/N Ratio
1	1	1	1	1	10.771	11.771	11.628	21.110
2	1	2	2	2	20.539	21.306	22.822	26.647
3	1	3	3	3	33.532	32.451	33.246	30.388
4	1	4	4	4	26.751	26.535	25.203	28.345
5	2	1	2	3	28.286	29.129	30.792	29.352

Experiment	Orthogonal Matrix L16(4)^5 Factor				Compressive Strength (MPa)			S/N Ratio
	Cement	Sand	SF	Water	I	II	III	
6	2	2	1	4	23.168	23.547	24.121	27.459
7	2	3	4	1	17.173	17.776	18.394	24.989
8	2	4	3	2	59.097	53.652	54.940	34.926
9	3	1	3	4	29.746	29.278	30.564	29.499
10	3	2	4	3	52.703	59.098	49.622	34.549
11	3	3	1	2	31.648	29.077	30.719	29.665
12	3	4	2	1	27.594	28.078	31.197	29.197
13	4	1	4	2	38.440	40.556	38.323	31.836
14	4	2	3	1	15.279	14.029	15.125	23.393
15	4	3	2	4	35.226	35.350	34.613	30.896
16	4	4	1	3	39.692	38.696	39.253	31.867
Average *S/N ratio*								29.007

Description: I = Sample 1, II = Sample 2, III = Sample 3

Table 8. Mean S/N Ratio Response Values at Each Factor Level.

Level	Cement	Sand	SF	Water
1	26.622	27.949	27.525	24.672
2	29.181	28.012	29.023	30.768
3	30.727	28.984	29.551	31.539
4	29.498	31.084	29.930	29.050
Range	4.105	3.135	2.404	6.867
Ranking	2	3	4	1

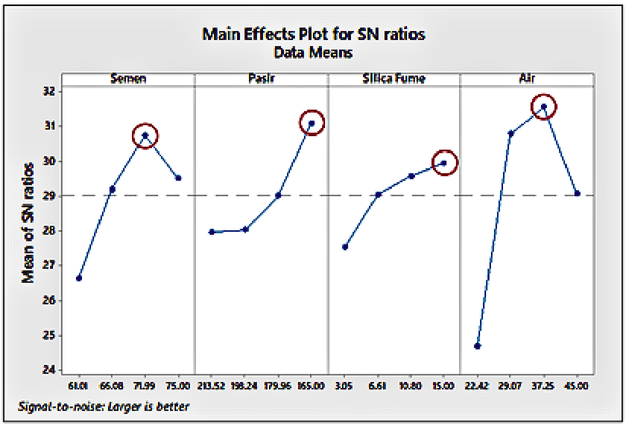

Fig. 2. *Main Effect Plot for S/N Ratio*

Based on the graph in **Fig. 2**, the highest S/N Ratio value was achieved at level 4 for the cement factor, level 2 for sand, level 4 for silica fume, and level 3 for water. As shown in **Table 8**, the water factor again demonstrates the most dominant influence on the S/N Ratio value, indicated by the highest range across levels. This evidence suggests that even small changes in water content can significantly affect the consistency of the mortar's compressive strength. A high S/N Ratio indicates that the compressive strength is not only high but also stable across replications at the corresponding mix composition. Therefore, precise control over water becomes crucial in silica fume-based mortar.

ANOVA for Mortar Compressive Strength. Analysis of variance (ANOVA) is used to evaluate the statistical significance and relative contribution of each factor in influencing the compressive strength of mortar. ANOVA compares the mean values and quantifies the contribution of each factor to the overall variability in the experimental data. The results of the analysis are presented in **Table 9**.

Table 9. ANOVA Results for Mortar Compressive Strength

Factor	DF (Degrees of Freedom)	SS (Sum of Squares)	MS (Mean Square)	F (F-Ratio)	P (P-Value)	Remarks	Status
Cement	3	1045.252	348.417	8.451	2.340×10^{-4}	F-Ratio>F-table	*significant*
Sand	3	783.210	261.070	6.332	1.518×10^{-3}	F-Ratio>F-table	*significant*
SF	3	527.922	175.974	4.268	1.139×10^{-2}	F-Ratio>F-table	*significant*
Water	3	3156.269	1052.090	25.519	6.262×10^{-9}	F-Ratio>F-table	*significant*

Error	35	1442.996	41.228
Total	47	6955.649	

To determine the significance of each factor, we conducted a comparison between the calculated F-value and the F-table value at a 5% significance level ($\alpha = 0.05$). With degrees of freedom for the factor ($df_1 = 3$) and for the error ($df_2 = 35$), the F-table value is 2.87. A factor is considered statistically significant if its F-value exceeds the F-table value. Based on the results, all factors (cement, sand, silica fume, and water) have F-values > 2.87, indicating that they significantly influence the compressive strength of mortar. The P-values, all below 0.05, further confirm the statistical significance of this finding. To assess the magnitude of each factor's influence, contribution percentages were calculated, as shown in **Table 10**.

Table 10. ANOVA Results and Contribution Percentage of Each Factor

Factor	DF (Degrees of Freedom)	Seq SS	Adj SS	Adj MS	F (F-Ratio)	P (P-Value)	Contribution	Contribution (%)
Cement	3	1045.252	1045.252	348.417	8.451	2.340×10^{-4}	15.027	15.027%
Sand	3	783.210	783.210	261.070	6.332	1.518×10^{-3}	11.260	11.260%
SF	3	527.922	527.922	175.974	4.268	1.139×10^{-2}	7.590	7.590%
Water	3	3156.269	3156.269	1052.090	25.519	6.262×10^{-9}	45.377	45.377%
Error	35	1442.996	1442.996	41.228			20.746	20.746%
Total	47	6955.649					100	100%
							SST	6955.649

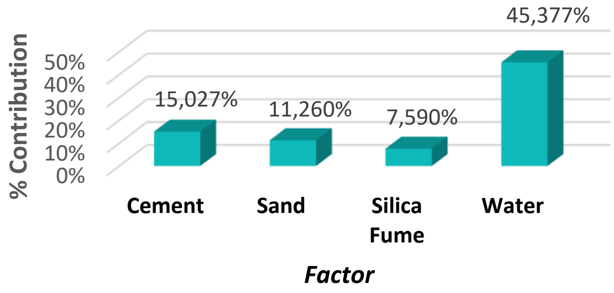

Fig. 3. Percentage Contribution of Each Factor to Mortar Compressive Strength

Fig. 3 illustrates the percentage contribution of each factor to the variation in mortar compressive strength based on ANOVA results. The graph shows that water has the most dominant contribution, followed by cement, sand, and silica fume. This dominance indicates that variations in water content significantly affect the resulting compressive strength. This is consistent with the role of water in the cement hydration process, where excessive water can reduce density and final strength, while insufficient water may hinder chemical reactions and workability of the mortar. Therefore, precise control of water content is essential to achieve optimal mortar performance.

According to the Taguchi method, an experimental design is valid if the error contribution is 50% or less, which means all important factors have been included in the analysis. In this study, the error contribution was 20.746%, indicating that no significant factor was overlooked and that the experimental design has accounted for all key variables affecting the compressive strength of mortar. The relatively large proportion of error is mainly caused by the wide variation in compressive strength values among the experimental combinations (e.g., 11.390 MPa in Combination 1 compared to 55.896 MPa in Combination 8), which increases the total variance and makes the proportion of error appear higher. Minor factors outside the four main variables may also have contributed to the error, such as variations in mixing and curing conditions, differences during specimen casting (e.g., non-uniform compaction while filling the molds), slight fluctuations in curing temperature or humidity, and potential inaccuracies in the compressive strength test due to equipment calibration or operator reading. Nevertheless, the influence of these factors is considered minimal, as evidenced by the consistent trend shown in the Main Effect Plot and the close agreement between predicted and confirmation test results. Therefore, the error contribution observed in this study is more likely due to the wide spread of compressive strength among combinations, rather than the influence of significant uncontrolled factors. Based on the analysis of the mean and S/N ratio, supported by the ANOVA results, the optimum factor combination that produces the highest compressive strength of silica fume-based mortar was determined. The optimum level for each factor is presented in **Table 11**.

Table 11. Optimum Setting Levels of Taguchi Experiment

Factor	Level	Setting Composition
Cement	3	71.99 grams
Sand	4	165.00 grams
Silica Fume	4	15.00 grams
Water	3	37.25 grams

Confirmation Experiment. The confirmation experiment was done as the last step of the Taguchi method to check that the best combination found really gives mortar performance that matches the expected results. This stage is essential to validate the optimization results obtained from the previous analysis. In this stage, three specimens (replications) were prepared using the material composition corresponding to the previously determined optimum combination. **Table 12** presents the compressive strength results of the three mortar samples after 28 days.

Table 12. Compressive Strength Test Results of Mortar from Confirmation Experiment at 28 Days

Sample	Cross-Sectional Area (mm²)	P (KN)	P (N)	Compressive Strength (MPa)	Mean Compressive Strength (MPa)
MK1	2576	143	143000	55.523	
MK2	2550	144	144300	56.588	57.138
MK3	2499	148	148200	59.304	

Based on the comparison results, it was found that the confidence intervals of the predicted condition and the confirmation experiment, both for the mean and the S/N ratio, overlap. This indicates that the compressive strength obtained from the confirmation experiment remains within the predictive bounds determined by the Taguchi method analysis. The validity of the prediction can be assessed at the intersection between the confidence interval of the optimum condition and the actual results, which means that the actual response does not deviate significantly from the expected value. Thus, the previously established optimum level combination is statistically valid and can be accepted as the best composition in this study. The comparison between the two confidence intervals is illustrated in **Fig. 4** and **Fig. 5** for the mean value and S/N ratio, respectively. Since the results of the confirmation test align with the expected values, the best mixture is seen as suitable for making silica fume-based mortar.

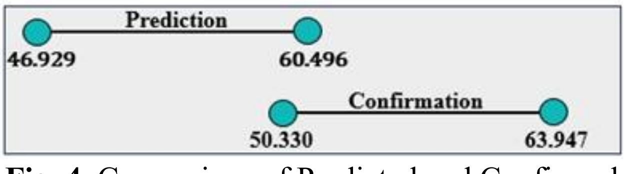

Fig. 4. Comparison of Predicted and Confirmed Confidence Intervals for the Mean

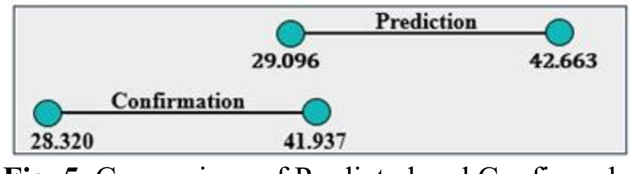

Fig. 5. Comparison of Predicted and Confirmed Confidence Intervals for the S/N Ratio

Compressive Strength Comparison of Optimized, Normal, and Reference Mortars. To evaluate the effectiveness of the optimized mortar mix using silica fume and the efficiency of the Taguchi method in producing high-performance mortar, a comparison was made between several types of mortar: optimized mortar, normal mortar with varying water-cement ratios (W/C), normal mortar using the optimum composition without silica fume, and reference mortar from previous studies [1, 3]. The results of the compressive strength tests for standard normal mortar (which has a cement-to-sand ratio of 1:3 and different water-cement ratios) are shown in **Table 13**, and the results for normal mortar made with the best mix that doesn't include silica fume are displayed in **Table 14**. **Fig. 6** illustrates the comparison of the average compressive strength values for all types of mortar.

Table 13. Compressive Strength Test Results of Normal Mortar

Sample	Mix Ratio (Cement : Sand)	Water Cement Ratio (W/C Ratio)	Mean Compressive Strength (MPa)
MN1	1 : 3	0.35	11.202
MN2	1 : 3	0.40	21.609
MN3	1 : 3	0.45	26.247
MN4	1 : 3	0.50	26.021

Table 14. Compressive Strength Test Results of Normal Mortar with Optimum Composition

Specimen	Setting Composition (grams)			Compressive Strength (MPa)	Mean Compressive Strength (MPa)
	Cement	Sand	Water		
NA	86.986	165.000	37.253	39.596	40,974
NB	86.986	165.000	37.253	40.488	
NC	86.986	165.000	37.253	42.836	

Based on the test results, the optimized mortar achieved the highest compressive strength of 57.14 MPa. In comparison, the regular mortar that didn't use silica fume and had different water-cement ratios (W/C) performed much worse, with strengths between 11.20 MPa and 26.02 MPa. The normal mortar, which used the same optimum composition but lacked silica fume, achieved a compressive strength of only 40.97 MPa. This comparison confirms that the inclusion of silica fume significantly enhances mortar strength, even when the base composition remains unchanged. This finding is supported by the ANOVA results, which indicate that silica fume contributes to strength improvement, although its percentage contribution is not as high as that of water. Silica fume works as a helpful material that reacts with calcium hydroxide to create more calcium silicate hydrate (C-S-H), which makes the mortar denser and stronger.

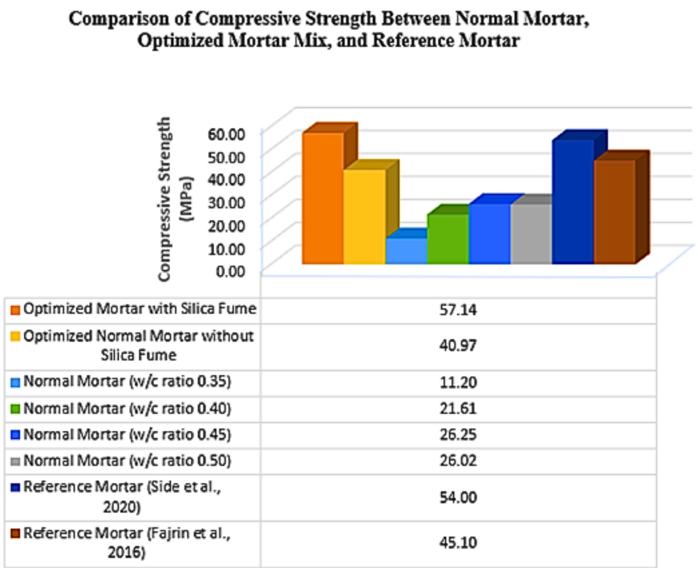

Fig. 6. Compressive Strength Comparison: Normal, Optimized, and Reference Mortars.

In an earlier study, they achieved a compressive strength of 54.00 MPa by using 18.52% silica fume instead of part of the binder [9], which is lower than the best result in this study (57.14 MPa). One reason for this disparity could be that the earlier study didn't treat water as a separate factor, so they didn't adjust its amount properly. However, the ANOVA analysis in this research indicated that water was the most important factor affecting compressive strength, making up 45.377%. This finding highlights the critical role of precise water content control through experimental design in improving mortar performance. Another study recorded a maximum compressive strength of 45.10 MPa with 10% silica fume addition [1]. Although it showed an increasing trend, the results had not yet reached the optimum point. This finding suggests that silica fume content ≥ 10% can still have a positive effect on mortar strength. The superior performance in this study is also attributed to the optimization strategy that sets all significant factors at their optimum levels.

The experimental method using the Taguchi approach has been successful in creating mortar that is stronger than what was achieved in earlier studies and regular mortar mixes. The optimized mortar has a compressive strength greater than 57 MPa, which meets and goes beyond the minimum requirement for Type M mortar [12], making it ideal for strong structural uses like repairs, precast parts, or infrastructure.

Conclusion

Based on the analysis and testing results, it can be concluded that the addition of silica fume as a pozzolanic material significantly improves the compressive strength of mortar. The optimum composition was obtained with a mixture of 71.99 grams of cement, 165 grams of sand, 15 grams of silica fume (equivalent to 20.84% of the cement weight), and 37.25 grams of water, resulting in a water-cement ratio (W/C) of 0.52. This composition produced a compressive strength of 57.14 MPa at 28 days of curing. ANOVA results showed that water was the most influential factor, contributing 45.377% to the compressive strength, followed by cement, sand, and silica fume. Accurate control of water content proved to be essential in achieving optimum strength. The confirmation experiment demonstrated that the actual performance fell within the predicted confidence interval, validating the optimum level combination derived from the Taguchi method. Additionally, comparisons with regular mortar and earlier research showed that using silica fume and the Taguchi method for optimization greatly improved the performance of the mortar. The optimized mortar has a compressive strength that is higher than the minimum needed for Type M mortar according to SNI 03-6882-2002, making it suitable for strong structures like load-bearing walls and precast elements. Therefore, using silica fume and the Taguchi method has been shown to effectively create strong mortar while making better use of cement. More studies are suggested to look into other important factors like tensile strength, elasticity, and durability in harsh conditions, and to investigate different additives that could help create more eco-friendly mortar.

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