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An Application of Taguchi Experiment Design Methods on Optimization of Mortar Mixture Composition With Silica Fume As Partial Substitute for Cement

at the **2019 International Conference on Mining & Environmental Technology (ICMET 2019)**
Organized by LPPM UMMAT and IAGI Nusra
Mataram, Indonesia July, 15th - 17th 2019

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IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: G N De Side *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **413** 012012

IOP Conf. Series: Earth and Environmental Science **413** (2020) 012012 doi:10.1088/1755-1315/413/1/012012

An application of Taguchi experiment design methods on optimization of mortar mixture composition with Silica Fume as a partial substitute for cement

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Abstract. The development of concrete technology in infrastructure also triggers the progressive cement manufacture, where cement production also contributes significantly to the emission of CO_2. To minimize the use of cement and increase mortar quality, the addition of additive substance material is needed with a quality control method. The purpose of this research is to establish the proportions of the materials with the optimum partial replacement of cement by silica fume to the compressive strength and physical properties of the 56 days old mortar using Taguchi Method design of experiment. This research uses 3 factors, which are silica fume proportion, sand proportion, and cement proportion. Each factor consists of 3 levels, with silica fume content is ±20% from the total weight of the cement. The mortar is based on 9 combinations of materials on the orthogonal matrix L9(3^4) created with dimensions of 50 x 50 x 50 mm cube. The results show that the optimum proportion is 150 gr of silica fume, 660 gr of cement and 1400 gr of sand which is equivalent to replacing 18.52 % cement with silica fume, which gains 54.00 MPa compressive strength, pH 9.75 and 5.369 % water absorption.

1. Introduction

In the technology of concrete, cement takes a crucial part in building infrastructure. The development of concrete technology in infrastructure growth also triggers the progressive cement manufacture, where cement production also contributes significantly to the emission of CO_2. According to ref [1], the production of cement engages the energy and intensive carbon process which constantly contributes to the emission of CO_2 to the environment, where cement industry releases 900 kg of CO_2 in each ton of cement production.

To minimize the use of cement and increase the mortar strength and quality, the addition of additive substance materials are needed. Silica fume is one of the materials of shotcrete technology (sprayed concrete), which is widely used to improve mix design. Shotcrete technology is currently developing in the mining field, where the use of silica fume can increase cohesiveness, which supports greater material strength [2]. The application of shotcrete technology is very suitable to strengthen the excavation walls of the mining area prone to landslides. Based on the research conducted by ref [3], concrete with 15% mixture of silica fume as the substitute of cement gains the higher compressive strength compared to 30% of fly ash. Silica fume has high ratio of water-cement and one of the very effective pozzolans. In 0% for 10% silica fume as the substitution, 0.5 kg silica fume can replace 1.5 to 2 kg cement in concrete without changing the compressive strength [4]. The influence of the partial substitution of cement with silica fume to mortar's physical and mechanical characteristics indicates that the addition of silica fume significantly affected water resistance level, which is higher. This is marked by the decreasing of water absorption, making the mortar in basic condition which is fairly safe for strengthening concrete column in it, and raise the compressive strength of the mortar [5].

There are treatments that have been started in previous researches yet to be conducted, especially in optimizing the mixture composition to achieve better mortar quality with effective and efficient materials composer. Therefore, it is important to conduct this research. This research is aimed to determine the proportion of the materials with optimal replacement of cement by silica fume toward the compressive strength and physical property with 56 days time span using a quality control method that is Taguchi Method or also known as Robust Design. It is an approach that has proven to be an efficient way to optimize the design and keeps the research cost at minimum level. In this experiment design, a set of orthogonal array is implemented on purposely to gain the optimum result considering the affecting factors condition and effective parameters in such a way that the researchers can obtain the expected target [6]. This research used 3 factors, i.e. silica fume proportion, sand proportion, and cement proportion, each factor consists of 3 levels, with silica fume content of ± 20% from the total weight of cement. The mixing mortar is based on 9 combinations of materials on the orthogonal matrix L9(3^4), made into a cube of 50 x 50 x 50 mm dimensions.

2. Method

2.1. The Taguchi Design Experiment Method

The result of the preliminary experiment is basic in determining the 3 level indicators that will be implemented in Taguchi Methods. The result of the preliminary experiment shows that the replacement of more than 15% of cement weight with silica fume gained the greatest compressive strength of mortar. The comparison of cement and sand is 30:70. The combination of that reference is applied as the value on medium level, which is equal with the replacement of 20% of cement weight with silica fume. The combination of material on level 2 is 120 gr of silica fume: 480 gr of cement: 1400 gr of sand. The value on high level (level 3), the higher value than level 2 is applied. Meanwhile on low level (level 1), the lower value than level 2 is applied. The results of the value in level factors are shown in Table 1, as well as the steps and specification in making the mortar sample that is implemented in this research as directed by reference [7].

Table 1. The total amount of level and factor level value

Factor	Level 1(gram)	Level 2 (gram)	Level 3 (gram)
Silica fume (A)	90	120	150
Cement (B)	300	480	660
Sand (C)	1200	1400	1600

3. Result and Discussion

3.1. The Result of Taguchi Experiment

The result of this experiment is obtained by conducting compressive strength test on a 56 days old mortar with the procedures refer to [8][9]. The compressive strength test is applied to the mortar based on the factor level combinations on orthogonal matrix. The orthogonal array, L9 (3^4) was chosen with 9 factor level combinations. The results are provided in Table 2 below.

Table 2. The Results of Mortar Compressive Strength Test

Exp.	Sectional Area of Object (mm^2)			Maximum Load (kN)			Compressive Strength (MPa)		
	A	B	C	A	B	C	A	B	C
1	2500	2450	2500	112	121	94	44,80	49,39	37,60

2	2500	2450	2500	120	134	130	48,00	54,69	52,00
3	2450	2500	2500	133	132	102	54,29	52,80	40,80
4	2500	2550	2500	103	109	106	41,20	42,75	42,40
5	2500	2500	2550	95	112	149	38,00	44,80	58,43
6	2500	2500	2450	133	112	130	53,20	44,80	53,06
7	2500	2500	2500	119	100	103	47,60	40,00	41,20
8	2500	2500	2500	121	132	140	48,40	52,80	56,00
9	2450	2500	2500	136	132	135	55,59	52,90	54,00

Description: A=1st sample, B=2nd sample, C=3rd sample

3.2. The Analysis of the Affecting Factor Toward the Mean of Mortar Compressive Strength

The mean of mortar compressive strength for each experiment is computed as soon as the value of mortar compressive strength is gained. The results are shown in Table 3. Table 4 presents the calculation results of the mean of mortar compressive strength for each of the factor levels.

Table 3. The Results of calculation of mean of mortar compressive strength

Orthogonal Matrix L9(3^4)				Compressive Strength (MPa)			Total	Mean
Experiment	Factor							
	A	B	C	A	B	C		
1	1	1	1	44.80	49.39	37.60	131.79	43.93
2	1	2	2	48.00	54.69	52.00	154.69	51.56
3	1	3	3	54.29	52.80	40.80	147.89	49.30
4	2	1	2	41.20	42.75	42.40	126.35	42.12
5	2	2	3	38.00	44.80	58.43	141.23	47.08
6	2	3	1	53.20	44.80	53.06	151.06	50.35
7	3	1	3	47.60	40.00	41.20	128.80	42.93
8	3	2	1	48.40	52.80	56.00	157.20	52.40
9	3	3	2	55.59	52.90	54.00	162.49	54.16
Total								433.83
Mean								48.20

Description: A = silica fume, B = cement, C = sand

Tabel 4. The response of mean of mortar compressive strength from affecting factor

	A	B	C
Level 1	48.26	42.99	48.89
Level 2	46.52	50.35	49.28
Level 3	49.83	51.27	46.44
Deviation	3.32	8.28	2.85
Rank	2	1	3

Description:
A = silica fume, B = cement, C = sand

Figure 1. Main effect plot mean of mortar compressive strength for factor A, B, C

Table 4 shows that factor B or cement is the most affecting factor toward the mean of mortar compressive strength since it is in the first place (rank 1). The decision of the factor rank on the response table is also needed to determine which factor that will be involved in the decision to predict the optimum condition value. When the prediction of the optimum condition is decided, not all of the factors can be used, but generally only half of the total of freedom degrees on orthogonal matrix that is used in the experiment. Since the orthogonal matrix L9(3^4) has 8 freedom degrees, we can take half of the total of freedom degrees as the important effect. However, this research only used 3 factors, therefore,the freedom degrees are 6, and half of 6 is 3. Thus, there are 3 factors that have important effect. The decision of which factors that have important effect can be seen from the rank of each factor on the response table. Since there are 3 important effects, the top three factors are taken. This research only used 3 factors, thus all of the factors in this research are used in determining the prediction value on optimum condition.

Based on the mean of mortar for every factor level in Table 4, the main effect plot is created for the mean of mortar compressive strength. The main effect plot is acquired for an easy analysis of the optimum level for the mean of mortar compressive strength. As presented in the graph in Fig.1, based on the characteristics quality, the larger is the better, thus the determination of maximum factor level is the one that has the largest mean of mortar compressive strength among the three levels in each factor. From the main effect plot in Figure 1, the optimum levels chosen to optimize mortar compressive strength is level 3 for factor A, level 3 for factor B, and level 2 for factor C.

3.3. The Analysis of Affecting Factors toward Signal to Noise Ratio (S/N Ratio)

Analyzing the effect of factors to S/N Ratio and the effect of factors of mean to mortar compressive strength is conducted to detect which factors likely influenced the decreasing of the variations and increasing of the means. S/N Ratio replaces the mortar compressive strength into a number until the greatest factor level can be determined to optimize the value of mortar compressive strength. The basic principle is the setting of factor level reaches the optimum condition if the value of S/N Ratio can be maximized. The result of the calculation for S/N value for each experiment is presented in Table 5.

Table 5. The result of calculation for the value of S/N Ratio for every experiment

Orthogonal Matrix L9(3^4)				Compressive Strength (MPa)			S/N
Experiment	Factor						
	A	B	C	A	B	C	
1	1	1	1	44.80	49.39	37.60	32.69
2	1	2	2	48.00	54.69	52.00	34.21
3	1	3	3	54.29	52.80	40.80	33.64
4	2	1	2	41.20	42.75	42.40	32.49
5	2	2	3	38.00	44.80	58.43	33.06
6	2	3	1	53.20	44.80	53.06	33.96
7	3	1	3	47.60	40.00	41.20	32.58
8	3	2	1	48.40	52.80	56.00	34.34
9	3	3	2	55.59	52.90	54.00	34.67
Total							301,62
Mean							33,51

Description: A = silica fume, B = cement, C = sand

Table 6. The value response of S/N ratio

	A	B	C
Level 1	33.51	32.59	33.66
Level 2	33.17	33.87	33.79
Level 3	33.86	34.09	33.09
deviation	0.70	1.50	0.70
Rank	2	1	3

A = Silica fume, B = cement, C = sand

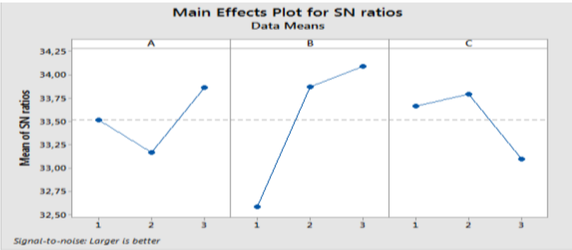

Figure 2. The Value of Signal Main Effect Plot to Noise Ratio (S/N Ratio) of Mortar Compressive Strength for Factor A, B,C

The results of the calculation for all of the factor levels are shown in Table 6. Table 6 shows that cement is the most affecting factor toward the variation of mortar compressive strength value since it is in the first place, followed by silica fume and sand. The value in Table 6, therefore, is made as the main effect plot for Signal to Noise Ratio (S/N Ratio) as Figure 2.

3.4. ANOVA Analysis for the Mean of Mortar Compressive Strength

Significance factors obtained by using F-ratio on the result of ANOVA has to be regarded. By regarding F-ratio, a factor can be classified as significantly affecting the mean of mortar compressive strength if F-ratio is greater than F-table [10], where F-table for α = 5% with factor freedom degree is (V1) = 2 and error freedom degree (V2) = 2, thus the F-table is (F0.05; 2; 2) = 19.00.

Table 7 shows that by comparing F-ratio, factor A has F-ratio 48.98 > F-table 19.00 (significant), factor B has F-ratio 366.06 > F-table 19.00 (significant), factor C has F-ratio 42,38 > F-table 19.00 (significant). In Taguchi method, if the percentage of error contribution is ≤ 50%, it can be concluded that the important factors affecting the response variable have been involved in that experiment [10]. Table 7 shows that the percentage of error contribution is 0.873%, which means that all of the factors significantly affecting the mean of mortar compressive strength have been involved in the experiment (under the Taguchi method terms and conditions for percentage of error contribution is ≤ 50%). The percentage of contribution for all of the factors is shown in Table 7.

Table 7. ANOVA and the percentage of contribution for every factor toward the mean of mortar compressive strength

Source	DF	SS	MS	F-ratio	SS'	ρ%
A	2	16.521	8.260	48.98	16.184	10.46%
B	2	123.478	61.739	366.06	123.140	79.63%
C	2	14.296	7.148	42.38	13.959	9.02%
Error	2	0.337	0.169		1.349	0.87%
SSt	8	154.632				100.00%

3.5. ANOVA Analysis for Mortar Compressive Strength's Signal to Noise Ratio (S/N Ratio)

To discover the factors significantly affecting the S/N Ratio of the mortar compressive strength or the controlling factor of variation distribution, the ANOVA analysis is needed. Table 8 shows that the factors significantly affecting the S/N Ratio of the mortar compressive strength are factor A (silica fume) with 12.815% contribution, factor B (cement) with 71.101% contribution, and factor C (sand) with 14.528% contribution. Whereas, for the percentage of error contribution is 1.556% which means that all of the factors significantly affecting the S/N Ratio of the mortar compressive strength have been involved in the experiment and has complied with the terms and conditions of Taguchi method. The percentage of error contribution is ≤ 50%.

Establishing the optimum level setting is done by adjusting to the desired factors that might be combined to minimize the variation and optimize the mortar compressive strength. The result of optimum level setting for all of the factors on the mortar experiment is presented in Table 9.

Table 8. ANOVA analysis

Source	DF	SS	MS	F-ratio	SS'	ρ%
A	2	0.729	0.36	33.94	0.708	12.81%
B	2	3.949	1.97	183.7	3.928	71.10%
C	2	0.824	0.412	38.34	0.802	14.52%
Error	2	0.021	0.011		0.086	1.55%
SSt	8	5.525				100.00%

Table 9. Optimum level setting

Factor	Level	Setting
A	3	150 gram
B	3	660 gram
C	2	1400 gram

A (Silica), B (Cement), C (Sand)

Based on the comparison of the confidence interval for confirming experiment and optimum condition for the mean of Taguchi experiment (Figure 3) and the comparison of confidence interval of S/N Ratio (Figure 4) showed that the expecting performance, by considering the confidence interval of optimum condition, is on confirmed condition interval. Therefore, the condition of optimum factor level can be accepted and the factor level combination is valid. The optimum mortar conditions have been compared with confirmation experiments, where the optimum condition confidence interval is in the confirmation condition interval. Then this condition is compared with the condition of the mortar without silica fume, shown in Figure 5.

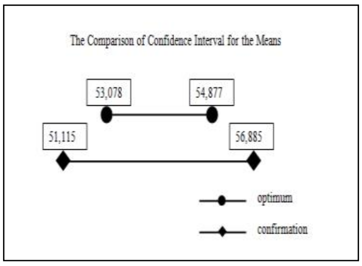

Figure 3. The Comparison of Confidence Interval for the Mean of Mortar Compressive Strength

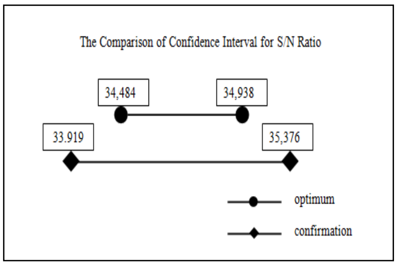

Figure 4. The Comparison of Confidence for S/N Ratio

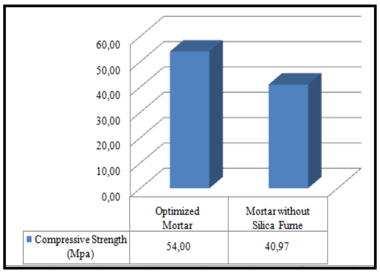

Figure 5. The result of compressive strength test graphics

3.6. *The Result of pH Mortar Test and Mortar Water Absorption Test*

The result of the pH test in Figure 6 showed that the pH for optimized mortar and mortar without silica fume are on basic condition, where optimized pH mortar is 9.75 and mortar without silica fume is 9.62. In addition, the pH of optimized mortar is 1.33% higher (more basic) than the mortar without silica fume.

According to the mean of mortar water absorption percentage in Figure 7, it can be concluded that by adding silica fume as the substitute for cement make the mortar has less water absorption than mortar without silica fume. Mortar water absorption on maximum condition with silica fume can reach 5.369%, meanwhile, mortar without silica fume has 8.875 %. water absorption.

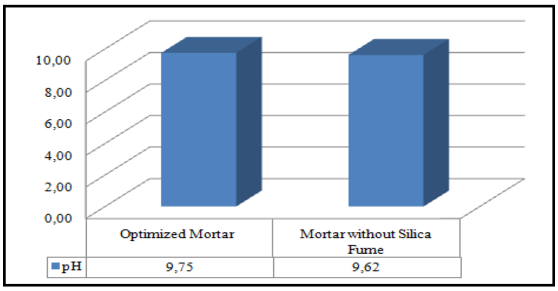

Figure 6. pH Test

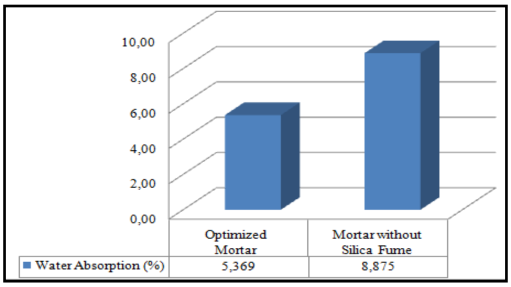

Figure 7. Water absorption test

4. Conclusion

Replacement of partial weight of cement with silica fume has a significant effect on compressive strength, pH and water absorption of mortar. Three factors that have a significant effect are silica fume proportion, cement proportion, and sand proportion. The most influential factor for compressive strength is cement proportion with a contribution of 79.6%, while the other two factors are almost the same at around 10% contribution. The optimum composition of mortar is 150 gr of silica fume: 660 gr of cement: 1400 gr of sand or equal to 18.52% silica fume replacement for cement that produces mortar compressive strength until 54.00 MPa. The compressive strength for mortar is 24.13% higher than the mortar without silica fume, i.e. as much as 40.97 MPa. The compositions produced mortar with an optimization compressive strength of 24% greater than the mortar compressive strength without silica fume. The ptimization results of the mortar pH obtained is 1.3% more basic and reduced water absorption by 39.5% compared to mortar without silica fume.

Further research using response variables other than compressive strength, such as tensile strength and physical properties and other mechanical properties of mortar, is required. On the manufacture of mortar with the addition of other additives is expected to increase the compressive strength of the mortar and become an alternative reference to other additives to replace the proportion of cement in the mortar mixture, to minimize the use of cement in the future.

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