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COMPRESSIVE STRENGTH OPTIMIZATION OF CONCRETE MIXED WITH WASTE CERAMICS AND FLY ASH

*Kenneth Jae T. Elevado[1], Joenel G. Galupino[1] and Ronaldo S. Gallardo[1]

[1]Civil Engineering Department, De La Salle University, Manila, Philippines

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ABSTRACT: Waste utilization has been one of the most vital aspects in the construction industry towards sustainability. It addresses the dilemmas that waste disposals face specifically the non-biodegradable materials such as damaged ceramics and industrial byproducts like fly ash. Recent studies have shown that damaged ceramics and fly ash obtain physical properties that are similar to the conventional aggregates of concrete and cement, respectively. In this study, experimental procedures were conducted to evaluate the compressive strength of concrete mixed with varying amount of fly ash and waste ceramics following the compressive strength test stipulated under ASTM C 39. Furthermore, strength development was also accounted through subjecting the concrete specimens to different curing periods. Response Surface Methodology (RSM) was used to provide the optimum combination of fly ash and waste ceramics that produces the most desirable compressive strength. The optimization results indicated that the optimum combination of waste ceramic tiles and fly ash replacements was 75% and 25% substitutions, respectively. This combination attains the maximum nominal compressive strength of 37.188 MPa. Similarly, the resulting Response Surface Methodology (RSM) model was validated to ensure that the model is acceptable.

Keywords: Compressive strength, Waste utilization, Fly ash, Ceramics, Concrete, Response surface methodology, Optimization

1. INTRODUCTION

Fly ash is generated during the combustion of coal power plants for energy production. Consequently, it is considered as an industrial byproduct and an environmental pollutant. Nevertheless, a lot of considerable researches about its utilization as a construction material have been conducted to somehow address the dilemmas that it pose [1]. In the Philippines, a considerable number of researches have supported the claim that fly ash possess properties that are comparable to cement [2-8]. On the other hand, ceramic tiles produced the highest amount of waste from the construction and demolition works worldwide with a production and manufacturing rate of 6.37 Billion of ceramics in Asia alone [9]. Similarly, recent researches have shown that waste ceramics are viable material in concrete production [8, 10-13].

Response Surface Methodology, also referred to as RSM, is used to develop relationships between a dependent variable, which is also referred to as the response, and associated independent variables [5]. It is used to optimize a response as a result of the influence of other independent parameters. The relationships could be graphically represented either in a two- or three-dimensional figure or in contour plots.

In this study, Response Surface Methodology (RSM) was used in optimizing the amount of fly ash and waste ceramic tiles to come up with the most desirable compressive strength of concrete. The graphical representation was in three-dimensional figure since three parameters were considered: the amount of fly ash and of waste ceramic tiles as replacements to cement and gravel, respectively, and the resulting compressive strength. In addition, the Response Surface Methodology (RSM) Model provided an equation that represents the compressive strength as a function of the amount of fly ash and of ceramic tiles based on the experimental data that were gathered. This equation was used to validate the model and ensure that the generated Response Surface Methodology (RSM) model is acceptable.

This study primarily aimed to optimize the compressive strength of concrete with partial substitutions of waste ceramic tiles and fly ash to the coarse aggregates and cement of concrete, respectively, using Response Surface Methodology (RSM).

2. METHODOLOGY

The preparation of the mix design of the specimens was in accordance with the American Concrete Institute standards [14].

The substitutions of waste ceramic tiles and fly ash to gravel as the coarse aggregate and Type 1 Portland Cement, respectively, were in terms of mass percentage replacements. The control mix did not incorporate any waste material –it only had pure cement and gravel. The percentage replacement of waste ceramic tiles to gravel considered these substitutions: 0%, 18.25%, 37.5%, 56.25% and 75% [7-12]. On the other hand, the substitution of fly ash to cement considered the following replacements: 0%, 12.5%, 25%, 37.5% and 50% [15-16].

All of the percentage replacements in the study were the output of the Design of Experiments (DOE) performed. This also produced a total of 17 mixes.

Although gravel was substituted with another material, it was still ensured that the grain size distribution of the coarse aggregates in all concrete mixes still adhere with the standards stipulated in the American Society for Testing and Materials (ASTM) through conducting rigorous sieve analysis in all mixes [17].

The raw materials were subjected to preliminary tests that are in accordance with the American Society for Testing and Materials (ASTM) prior to the preparation of the mixes. These tests include the derivation of the following: moisture content, specific gravity, absorption, unit weight and voids of aggregates [18-20]. In addition, a chemical analysis of the Class F fly ash used in the experiment was also undertaken [21]. The results of these tests are shown in Table 1.

Table 1. Summary of material properties [7, 9]

Description	Results
Dry rodded density of gravel	1567.839 kg/m^3
Specific Gravity of Cement	3.150
Specific Gravity of gravel	2.812
Specific Gravity of sand	2.505
Moisture Content of gravel	0.349%
Moisture Content of sand	1.566%
Absorption of gravel	1.639%
Absorption of sand	2.765%
Fineness modulus of Sand	2.760
Chemical Compounds of Fly Ash	
Silicon Dioxide (SiO_2)	49.6%
Aluminum Trioxide (Al_2O_3)	26.7%
Ferric Oxide (Fe_2O_3)	4.26%
Calcium Oxide (CaO)	8.2%
Magnesium Oxide (MgO)	5.9%
Sulfur Trioxide (SO_3)	0.83%

After obtaining the necessary preliminary data found on Table 1, the concrete mix was prepared. A water-cement ration of 0.478 was considered by having a target nominal strength of 28 MPa. The mixing water used in the concrete mix was 184 kilogram per cubic meter of concrete. This was derived from considering 19.0 mm maximum size of aggregate and 25-100 mm slump. Three curing periods (7, 28 and 56 days) were considered and total of 306 specimens were prepared in this study.

Furthermore, compressive strength tests were conducted after each specified curing period. The average cross-sectional area of the specimen was measured. A load was applied to the specimen, and the maximum load that the specimen was able to carry was recorded. With this, the resulting compressive strength was computed by simply dividing the maximum compressive load that the specimen was able to carry by its average cross-sectional area.

Moreover, a systematic way of labeling the mix design was introduced through providing Mix IDs. The labels "F" and "C" was used to refer to the percentage of fly ash and waste ceramic tiles to the concrete mix, respectively. For instance, Mix ID "F37.5C18.75" refers to the concrete mix with 37.5% fly ash, 62.5% Type 1 Portland Cement, 18.75% waste ceramic tiles and 81.25% gravel. The summarized list of Mix IDs is shown in Table 2.

Table 2. Mix IDs of the specimen used [7, 9]

Mix No.	Mix ID	Fly Ash Content	Ceramic Tiles Content
M1	F0 C0	0.00%	0.00%
M2	F50 C0	50.00%	0.00%
M3	F50 C 37.5	50.00%	37.50%
M4	F25 C37.5	25.00%	37.50%
M5	F37.5 C 18.75	37.50%	18.75%
M6	F25 C0	25.00%	0.00%
M7	F25 C 18.75	25.00%	18.75%
M8	F12.5 C 37.5	12.50%	37.50%
M9	F37.5 C37.5	37.50%	37.50%
M10	F0 C37.5	0.00%	37.50%
M11	F37.5 C56.25	37.50%	56.25%
M12	F12.5 C 18.75	12.50%	18.75%
M13	F25 C56.25	25.00%	56.25%
M14	F12.5 C56.25	12.50%	56.25%
M15	F50 C75	50.00%	75.00%
M16	F0 C75	0.00%	75.00%
M17	F25 C75	25.00%	75.00%

This study optimized the compressive strength of all mixes using Response Surface Methodology (RSM), the values that were obtained from the RSM model were treated as the theoretical data. Response Surface Methodology, also referred to as RSM, is used to develop relationships between a dependent variable or a response of interest, y, and associated independent variables, x_1, x_2, … , x_n. It is used to optimize a response because of the influence of other independent parameters. The relationships could be graphically represented either in a three-dimensional figure or in contour plots. Eq. 1 shows the simplest form of the RSM:

$$y = f(x_1, x_2) + \varepsilon \quad (1)$$

Where:
y = dependent variable, response;
x_1, x_2 = independent parameters;
f (x_1, x_2) = response surface;
ε = experimental error observed.

In this study, RSM was used in optimizing the amount of fly ash and waste ceramic tiles to come up with the most desirable compressive strength of concrete. The graphical representation was in three-dimensional figures since three parameters were considered: the amount of fly ash and of waste ceramic tiles as replacements to cement and gravel, respectively, and the resulting compressive strength. In addition, the RSM Model Data provided an equation that represents the compressive strength as a function of the amount of fly ash and of ceramic tiles based on the experimental data that were gathered. Validations were conducted through various statistical tools that are discussed in the succeeding chapters.

The dependent and independent variables are continuous. In the study the dependent and independent variables are shown in Table 3:

Table 3. Input and Output Variables

Dependent Variable(s)	Independent Variable(s)
1. 7-Days Compressive Strength 2. 28-Days Compressive Strength 3. 56-Days Compressive Strength	1. Fly Ash % 2. Ceramics %

3. RESULTS & DISCUSSION

3.1 Compressive Strength

Compressive strength tests followed the standard methods stipulated under ASTM C 39 to ensure the results garnered are correct. The conventional mix attained its target nominal strength (28-Day) with 28.302 MPa. The early and late compressive strengths of the conventional mix at 7 and 56 days of curing periods were 21.645 MPa and 28.722 MPa, respectively. Among all modified mixes, F50C0 and F25C75 resulted to the least and highest compressive strengths at all ages with 26.343-MPa and 38.112-MPa nominal strengths, respectively. The complete compressive strengths of all mixes are shown on Table 4.

Compressive strength tests were conducted at three curing periods: 7 days, 28 days and 56 days. A sample plot is shown in Figure 1. This was done in order to have a representation of the compressive strengths of all mixes at early, nominal and late stages for further analysis. The results are shown in Figure 2.

Table 4. Compressive strengths of all mixes [7, 9]

MIX No.	MIX ID	Compressive Strengths (MPa)		
		7-day	28-day	56-day
M1	F0 C0	21.65	28.30	28.72
M2	F50 C0	19.07	26.34	28.41
M3	F50 C 37.5	21.68	27.85	33.88
M4	F25 C37.5	27.29	37.21	39.20
M5	F37.5 C 18.75	24.97	32.14	35.44
M6	F25 C0	25.51	33.88	38.09
M7	F25 C 18.75	27.78	34.51	38.95
M8	F12.5 C 37.5	30.96	37.44	41.57
M9	F37.5 C37.5	25.07	33.83	35.97
M10	F0 C37.5	29.00	32.14	38.00
M11	F37.5 C56.25	27.46	34.49	38.32
M12	F12.5 C 18.75	26.00	34.06	37.90
M13	F25 C56.25	25.15	34.17	38.28
M14	F12.5 C56.25	27.53	27.23	36.36
M15	F50 C75	24.53	33.21	41.78
M16	F0 C75	24.86	33.95	39.66
M17	F25 C75	32.06	38.11	44.70
Minimum		**19.07**	**26.34**	**28.41**
Maximum		**32.06**	**38.11**	**44.70**

All mixes had an increasing nominal compressive strength when waste ceramic tiles replacement was also increased except for the mix with 12.5% fly ash replacement, where the strength decreased from 37.5% to 56.25% waste ceramic tiles substitution.

In terms of cement variation, all combinations showed an increasing nominal strength up to an optimum amount. Based from the experimental data, all combinations have shown an optimum amount of 20% to 30% fly ash replacement except for the mix with 37.5% waste ceramic tiles replacement, which had an optimum amount of 10% to 20% fly ash substitution. Moreover, all combinations with 50% fly ash substitution attained less compressive strengths relative to mixes with 0% fly ash replacement.

Based from the Student's T-test conducted with 95% significance level, the compressive strengths of F50C0, F50C37.5 and F12.5C56.25 were found out to be statistically similar to the conventional mix at the 28th day-period. These mixes had 2-MPa decrease in strength than the conventional mix.

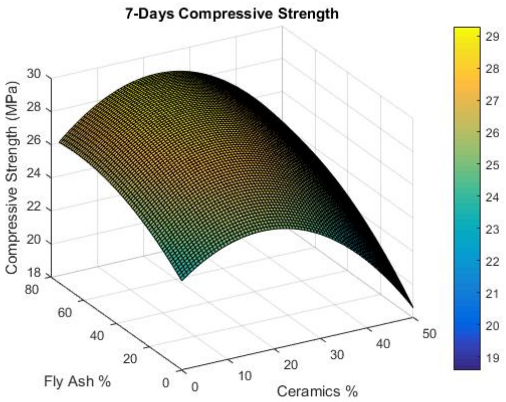

Figure 1. 7-Day Compressive Strength Modelling [7, 9]

Pozzolanic reaction has played a major role in the strength development of the modified mixes considering that both waste materials used, ceramic tiles and fly ash, possessed pozzolanic properties as inferred from the related literatures. Aside from F50C0, all compressive strengths at the 56-day period exceeded the strength of the conventional mix. On the other hand, F0C37.5 and F12.5C56.25 produced compressive strengths less than F0C0 at the 28-day period. In terms of the modified mixes, 30% to 70% increase in strength was observed from the 7 to 56-day span.

With regards to the bonding of the aggregates, the particles of the cement paste of all mixes were fibrillating from 7 to 56 days of curing periods. This allowed the cement paste to better bond with the other aggregates. However, when fly ash was introduced in the mix, the particles of cement paste became more spherical –as the percentage of fly ash replacement was increased, more spherical particles were also observed. These spherical particles could have caused a weaker bonding among the aggregates thus providing weaker strength.

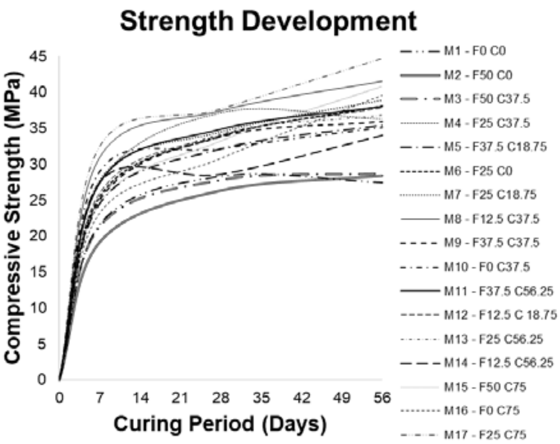

Figure 2. Strength development of the mixtures [7, 9]

Optimization results have indicated that the optimum combination of fly ash and waste ceramic tiles replacements at the 28th day-period was 25% fly ash and 75% waste ceramic tiles with 0.92 desirability to attain the maximum compressive strength of 37.188 MPa.

3.2 *Response Surface Methodology*

In optimizing the nominal compressive strengths in the study, the screened data from each mix was considered. A three-dimensional Response Surface Methodology (RSM) model was generate. Similarly, the percentage replacements of fly ash and waste ceramic tiles (labeled "%FA" and "%WCT", respectively) were accounted along with its corresponding treated data. In terms of the optimization constraints, %FA and %WCT were maintained to be in range at 0 to 0.5 and 0 to 0.75, respectively, while maximizing the compressive strength (labeled "f'c"). Table 5 shows the summary of the optimization constraints considered.

Table 5. Strength Optimization Constraints

Name	Goal	Lower Limit	Upper Limit
% FA	is in range	0	0.5
% WCT	is in range	0	0.75
f'c	maximize	26.3431	38.1124

The three-dimensional RSM Model could predict the resulting compressive strength given the percentage replacements of fly ash and waste ceramic tiles. With 0.92 desirability, Eq. 2 was the generated equation from the model.

$$\begin{aligned} f'c = {} & 30.01565 + 33.35915\ \%FA \\ & + 0.98742\ \%WCT \\ & + 8.83664\ \%FA\ \%WCT \\ & - 79.86914\ (\%FA)^2 \\ & + 2.53592\ (\%WCT)^2 \end{aligned} \tag{2}$$

Where:
f'c = predicted strength (MPa);
%FA = percentage of fly ash;
%WCT = percentage of waste ceramic tiles.

The statistical equation is further illustrated on a three-dimensional model in Fig. 3 Based from the model, the effects of cement and coarse aggregates modification as previously discussed were also observed –an increase in %FA resulted to an increase in strength up to an optimum amount and an increase in %WCT yielded an increase in strength. The combination of both waste materials was gradually producing higher compressive strengths.

Although the same trend was observed

when the data with outliers were considered, performing data screening somehow increased the level of desirability of the model by up to 3%. Its implication on the compressive strength is further discussed in the succeeding pages.

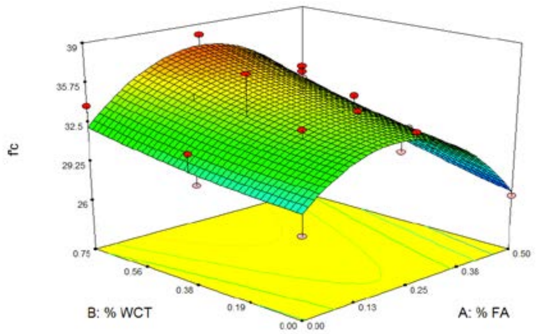

Fig. 3. RSM Model of compressive strength without outliers.

Moreover, Table 6 shows the top three solutions for the combinations of factors:

Table 6. Top solutions for the combination of factors (strength optimization)

No.	% FA	% WCT	f'c	Desirability	Remarks
1	0.25	0.75	37.1875	0.921	Selected
2	0.26	0.75	37.1804	0.921	-
3	0.24	0.75	37.1712	0.92	-

Considering the optimization constraints, the optimum combination of %FA and %WCT in attaining the maximum compressive strength was 25% of fly ash and 75% of waste ceramic tiles. This combination was found out to be the top solution among the top three solutions presented on Table 6, which yielded 37.188-MPa strength. The same combination was observed to be the maximum strength among the experimental data.

Moreover, performing various data screening did not just increase the level of desirability of the model. It also increased the optimum strength by around 2%. Since the primary aim of optimizing the compressive strength was to come up with the highest strength, the RSM Model without outliers as shown in Figure 3 was considered in the study for its strength optimization.

Pearson's Correlation was used in the evaluation the correlation between the experimental and the theoretical data. On the other hand, an equality line was projected when these data were plotted to have a graphical representation in assessing the validity of the models.Using Pearson's Correlation, the theoretical vs experimental data were plotted and the coefficient of correlation, denoted as "R", was determined. Fig. 4 show the graphs for strength optimization generated along with the respective R-values.

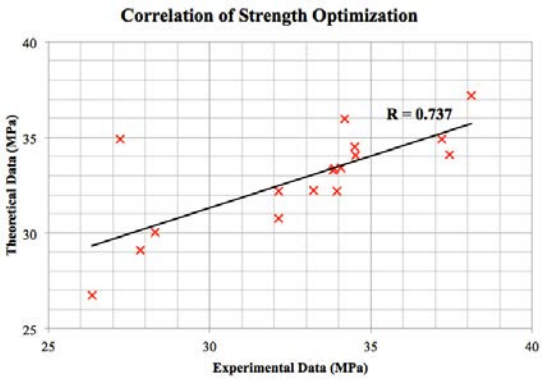

Fig. 4. Correlation of strength optimization

The coefficient of correlation between the experimental data and the theoretical data based on the generated RSM model for strength optimization was 0.737. Based on Pearson's Correlation criteria, this signified that the two sets of data have a strong correlation. Thus, it could be said that the generated quadratic RSM model is statistically acceptable.

4. CONCLUSIONS & RECOMMENDATIONS

Compressive strength tests followed the standard methods stipulated under ASTM C 39 to ensure the results garnered are correct. The conventional mix attained its target nominal strength (28-Day) with 28.302 MPa. The early and late compressive strengths of the conventional mix at 7 and 56 days of curing periods were 21.645 MPa and 28.722 MPa, respectively. Among all modified mixes, F50C0 and F25C75 resulted to the least and highest compressive strengths at all ages with 26.343-MPa and 38.112-MPa nominal strengths, respectively.

All combinations showed an increasing nominal strength up to an optimum amount. Based from the experimental data, all combinations have shown an optimum amount of 20% to 30% fly ash replacement except for the mix with 37.5% waste ceramic tiles replacement, which had an optimum amount of 10% to 20% fly ash substitution. Moreover, all combinations with 50% fly ash substitution attained less compressive strengths relative to mixes with 0% fly ash replacement.

Pozzolanic reaction has played a major role in the strength development of the modified mixes considering that both waste materials used, ceramic tiles and fly ash, possessed pozzolanic properties as inferred from the related literatures. Optimization results have indicated that the optimum combination of fly ash and waste ceramic tiles replacements at the 28th day-period was 25% fly ash and 75% waste ceramic tiles with 0.92 desirability to attain the maximum compressive strength of 37.188 MPa. Therefore, a valid RSM Model was able to predict the resulting compressive strength given the percentage replacements of fly ash and waste ceramic tiles.

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