Optimization of Eco-friendly Pavement Concrete Mixture Using Response Surface Methodology

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Abstract. The premature deterioration of pavement concrete structures under loading has led to the development of high-performance concrete. It is required that pavement concrete must have high strength properties because it is subjected to destructive traffic loads. The main purpose of the present study is to design optimum Eco-friendly concrete mixtures containing different amount of silica fume used in rigid pavement matching Iraqi requirements by using Response Surface Methodology (RSM). The experiments were designed using a thirty mixtures with four factors, namely, the cement content 300, 350 and 400 kg/m3, water/cementitious ratio of 0.3, 0.40 and 0.5, three different amount of fine/ course ratios0.3,0.4 and 0.5, and 0, 5, and 10% Silica fume by weight of cement. The results stated that, cement amount and silica fume ratios are the higher factors affecting the mechanical properties followed by fine- to-course aggregate and water- to-cementisous ratio. Furthermore, good correlation between the adopted variables and mechanical properties (compressive and flexural strength) was found through statistical models, where the correlation coefficients R2 for all models were greater than 0.95. finally, the optimal components to design concrete mixtures used in pavement that having compressive strength of (>30 Mpa) and flexural strength of (> 4.1 Mpa) where found to be: cement 365 kg/m3,silica fume 3.9%,F/C ratio of 0.3, and W/C ratio of 0.5.

Keywords: concrete pavement; mechanical properties; RSM; Eco-friendly concrete

1. Introduction
Concrete is widely used in several kinds of road structures such as pavements, slabs of approach and decks of bridges. In current years, the increase in both the high traffic level and the axle loads has raised worldwide demands for the concrete pavement. Although using the useful additives, the initial cost and total cost of a concrete pavement may be reduced, an economic study has to be done. Portland cement (PC), the primary binder, is amongst others the most energy-intensive component in conventional concrete. Manufacturing cement contributes 8 percent to CO2 emissions [1]. However, binder-rich (increased PC content) mixture compositions are required especially for high-performance concretes (HPC), which increase the risks of environmental unfriendliness and dimensional instability [2].

As mentioned above, despite attention about the manufacture of large quantities of (PC), the inclination of many current studies is to produce sustainable concrete mixtures [3–5]. The idea of producing more Eco-friendly concrete can be achieved by minimizing the amount of CO2 [6, 7]. Rich cement mixtures resulting in an increase in concrete strength. It may, in turn, cause shrinkage. Concrete may induce stresses that exceed its tensile capacity; cracks may therefore appear [8]. There is common agreement that the compressive strength is 1/10 the maximum tensile strength. Brittleness and dimensional instability are considered to be negative properties in concrete. Precautions must be
taken to control cracking in a concrete pavement by removing or at least reducing cracks. The cracks decrease service life and increase maintenance costs [9]. The use of silica fume as part of concrete binders, particularly in the production of high-performance concrete and high strength. In addition, their use as mineral admixtures as partially contributes to sustainable concrete construction [10–12]. Incorporation silica fume into concrete led to modification the role of concrete aggregate [13]. It's reported that increasing silica fume contributes the concrete strength regarding compressive [14] and flexural strength [15].

The design of experiments (DoE) is one of ways to saving the time and costs by which can reduce the number of tests (trials). In the other word, the DoE seeks the choosing of most proper points (tests) in which the response (output) must be well examined. Thus, the use of experiment design has a great rule in selecting the connected response surface test [16]. Furthermore, the response surface methodology (RSM) has the ability to determine the impact between the independent factors, unlike other methods that takes the effect of each variable separately.

2. Purpose of the study
Cost is sometimes more important than quality, but the quality is the way to reduce the cost. To get this goal, the main purpose of the present study is to design optimum Eco-friendly concrete mixtures containing different amount of silica fume used in rigid pavement matching Iraqi requirements by using Response Surface Methodology (RSM). The objective of this study is both to determine the effect of cement content, silica fume (SF), water/cementations (w/c) material ratio and fine/course (F/C) aggregate ratio on the Modulus of Rupture of the concrete pavement and finding the optimum conditions for the most cost effective mix design

3. Materials Used, Test, and Mixture Design
3.1 Material
3.1.1 Cement
The cement used throughout this work was Ordinary Portland Cement Type I (Tasluga Factory). It was contained in airtight plastic containers to prevent exposure to various atmospheric conditions. The chemical analysis and the findings of the physical tests complied with the Iraqi standard No. 5/1984[17]. The specific surface area (Blaine method), initial setting time, final setting time, soundness, compressive strength of the mortar at 3 days and compressive strength of the mortar at 7 days of the used cement were 394 m2/kg 115min, 4.87hour, 0.03%, 16.07 N/mm2 and 24.27 N/mm2 respectively. The CaO, SiO2, Al2O3, Fe2O3, MgO, SO3, and L.O.I, of the used cement were 62.27%, 20.75%, 4.22%, 5.34%, 1.74%, 2.07%, and 1.86 respectively. All chemical tests were made by Baghdad University-Engineering collage / Laboratories of Consulting Engineering Bureau.

3.1.2 Fine aggregate
The natural river sand from Al-Ukhaider region is used in concrete mix so as to achieve the mid-range gradient specification. It was separated into different sizes by sieve analysis equipment to choose optimum grading according to Iraqi specification (I.Q.S 45-1984) and it is chosen to match (SORB /R8,2003)[18]. The specific gravity, absorption, sulfate content and finesse modulus were 2.6, 0.85%, 0.254% and 2.5% respectively. The particle size distribution is shown in Figure (1). All physical properties of fine aggregate were made at Material Laboratory in Engineering College of Mustansiriya University, except Sulfate content (SO3), %, test was made by Baghdad University-Engineering collage / Laboratories of Consulting Engineering Bureau.
3.1.3 Coarse Aggregate
The crushed gravel from AL-Niba'ee region is used in concrete mix so as to achieve the mid-range gradient specification. The gravel was separated into different sizes by sieve analysis equipment to choose optimum grading according to Iraqi specification (I.Q.S 45-1984) and it’s chosen to match (SORB/R8, 2003). Then, the aggregate was flushed and cleaned by water. The specific gravity, absorption, sulfate content and material passed from sieve No.200 (75 µm) were 2.63, 1.68%, 0.071%, and 0.0% respectively. The grading of coarse aggregate is shown in Figure (2).

3.1.4 Mixing Water
Water is an essential constituent of concrete mixture; it reacts chemically with Portland cement (hydration) to produce the desired concrete properties. Potable water was used in the Casing and Curing process.

3.1.5 Silica Fume
Micro Silica material has been used in concrete mixtures with different cement weight ratios. Micro-Silica fume (SF) is a pozzolanic material which is very active. It is a by-product of silicon or ferro-silicium metal products. Of the silica fume used, the SiO2, SO3, and L.O.I were 94.5 percent, 0.25 and 3.8, respectively. The results show that the SF used satisfies ASTM C1240 specifications [19].

Figure 1. Gradation for Fine Aggregate.

Figure 2. Gradation for coarse aggregate.
3.2 Sample Preparing and Test
According to the main purpose of this investigation, prism specimens measuring 100×100×500 mm were cast and then tested under four-point bending/loading to determine the flexural parameters: flexural strength based on Modulus of Rupture (MOR) [20]. Also, cubic specimens with a dimension of 100 mm were prepared for compressive strength evaluation. After 24 hours, both prismatic and cubic specimens were moved to be further cured in water until 7, 28 and 90 days were finished.

3.3 Mixtures design
Four factors are adopted in the present study namely; cement content, silica fume (SF), water/cementations (w/c) ratio and fine/course (F/C) aggregate ratio. Factors and their levels are given in Table (1). Response Surface Methodology (RSM) is used for determining and optimizing the test results. Experimental parameters and their levels in the light of preliminary experience were sought. Response surface methodology (RSM) is a procedure that broadly adopted in optimizing the performance of system [21]. Thirty runs (mixtures) were used due to the four factors with three levels each (Table 2). The 30 mixtures were designed according to the Central Composite Design (CCD) which is the most famous of every single quadratic design and normally utilized in (RSM).

4. Experimental Results
As mentioned before, four variables: cement amount, silica fume, W/C, and F/C ratios were adopted to investigate their effects on the mechanical properties, compressive and flexural strength response. The summary results of the above variables are listed in Table 3. For Laboratory testing program, two response types have been explored so as to assess the mixtures proposed utilizing (CCD), to be specific: Compressive strength and flexural strength. In addition, the cost and the CO2 emissions for each mixture were estimated to take into account designing concrete mixture have low cost and low cement content (i.e low CO2 emissions). The CO2 emissions associated with the manufacturing of the binder materials used in this study were calculated based on values provided by the Environmental Protection Agency [22,23]. The summary results of laboratory tests for mechanical properties, CO2 emissions and costs are shown in Table 3.

4.1 Screening and variables analyses
Screening analysis is a powerful tool used to investigate the influence of a set of variables on predicted compressive and flexural strength to choose the most essential contributing variables. The design of experiment (DOE) software was used in this paper which its outcomes are presented using a Pareto chart as shown in Figures 3. This figure shows the most essential parameters affecting compressive and flexural strength properties by order. Regarding compressive strength, which is shown in Figure 3 (a), the cement has the most significant impact followed by silica fume, fine-to-course aggregate ratio (F/C), water-to-cementitious ratio (W/C). Same behavior for flexural strength is observed as illustrated in Figure 3(b).

4.2 Effect of cement and silica fume on mechanical properties
After doing the screening, it is found those cement amount and silica fume ratios are the higher factors affecting the mechanical properties. The experimental results shown in Figure 4(a) indicated that compressive strength at higher amount of cement and silica fume showed more compliant. In addition, the flexural strength is affected by increasing both the cement and silica fume (see Figure 4(b)).

5. Prediction of Mechanical properties behavior and ANOVA analysis
By using response surface methodology (RSM), the predicted models for compressive and flexural strength were found. This method is broadly adopted in optimizing the performance of system. In the present study, design of expert (DOE) software program was used for the statistical analysis and mathematical modelling. Analysis of variance ANOVA is valuable way of assessing the fitted model. ANOVA was conducted in order to achieve the interaction between the different parameters and the impact of each individual parameter. For a respectable model fit, the coefficient of determination
ought to be a minimum of 0.80. A high R² value near to 1.00 demonstrates a desired and reasonable agreement between the observed and calculated results. As shown in Table 4, p-values which are less than 0.0001 indicate that the model is significant for 95% confidence intervals. The R² values specify that there is a good correlation between actual and predicted values.

Table 1. The four factors and the levels utilized in the study.

| Factors                          | Levels         |
|----------------------------------|----------------|
|                                  | low level | mean level | high level |
| Cement (kg/m³)                   | 300       | 350        | 400        |
| water/cementations Ratio         | 0.3       | 0.4        | 0.5        |
| Silica fume                      | 0         | 0.05       | 0.1        |
| fine/course aggregate            | 0.3       | 0.4        | 0.5        |

Table 2. Array of experimental design by RSM.

| Run (Mixture No.) | Cement | W/c | F/c | SF |
|-------------------|--------|-----|-----|----|
| 1                 | 350    | 0.4 | 0.4 | 0  |
| 2                 | 350    | 0.4 | 0.4 | 0.1|
| 3                 | 350    | 0.4 | 0.3 | 0.05|
| 4                 | 400    | 0.5 | 0.5 | 0.1|
| 5                 | 300    | 0.3 | 0.3 | 0.1|
| 6                 | 350    | 0.4 | 0.4 | 0.05|
| 7                 | 350    | 0.4 | 0.4 | 0.05|
| 8                 | 400    | 0.5 | 0.3 | 0.1|
| 9                 | 350    | 0.5 | 0.4 | 0.05|
| 10                | 300    | 0.3 | 0.5 | 0.1|
| 11                | 350    | 0.3 | 0.4 | 0.05|
| 12                | 400    | 0.3 | 0.3 | 0.1|
| 13                | 350    | 0.4 | 0.4 | 0.05|
| 14                | 350    | 0.4 | 0.4 | 0.05|
| 15                | 400    | 0.3 | 0.5 | 0.05|
| 16                | 400    | 0.4 | 0.4 | 0.05|
| 17                | 300    | 0.5 | 0.5 | 0.05|
| 18                | 400    | 0.3 | 0.3 | 0.05|
| 19                | 400    | 0.5 | 0.3 | 0.05|
| 20                | 300    | 0.3 | 0.5 | 0.05|
| 21                | 400    | 0.3 | 0.5 | 0.05|
| 22                | 300    | 0.5 | 0.3 | 0.05|
| 23                | 300    | 0.5 | 0.3 | 0.05|
| 24                | 400    | 0.5 | 0.3 | 0.05|
| 25                | 300    | 0.4 | 0.5 | 0.05|
| 26                | 350    | 0.4 | 0.4 | 0.05|
| 27                | 350    | 0.4 | 0.4 | 0.05|
| 28                | 350    | 0.4 | 0.5 | 0.05|
| 29                | 300    | 0.3 | 0.3 | 0.05|
| 30                | 300    | 0.5 | 0.5 | 0.1|
Table 3. Summary of results of mechanical properties

| Run (Mixture ID) | Kg CO2-e/m3 | Total Cost (US$/ m3) | Compressive Strength (Mpa) | Flexural Strength (Mpa) |
|-----------------|-------------|----------------------|----------------------------|------------------------|
|                 |             |                      | 7-days 28-days 90-days    | 7-days 28-days 90-days |
| 1               | 351.8       | 54.1                 | 22.6 29.7 45              | 2.51 3.39 5.8          |
| 2               | 352.9       | 97.3                 | 28.1 36.8 55              | 3.1 4.2 7.1           |
| 3               | 353.75      | 75.0                 | 25.7 33.6 50              | 2.83 3.83 6.5         |
| 4               | 405.1       | 107.2                | 31.2 40.1 60              | 3.44 4.53 7.7         |
| 5               | 305.7       | 87.2                 | 23.4 30.8 46              | 2.55 3.54 6.0         |
| 6               | 356.85      | 75.7                 | 27.4 35.2 53              | 3.0 4.0 6.8          |
| 7               | 357.85      | 75.7                 | 26.8 34.3 52              | 2.9 3.9 6.7          |
| 8               | 408.9       | 106.1                | 35.1 45.7 69              | 3.92 5.16 8.8         |
| 9               | 359.95      | 75.4                 | 23.4 30.1 45              | 2.54 3.43 5.8         |
| 10              | 310.9       | 88.6                 | 22.6 29.6 44              | 2.45 3.4 5.8          |
| 11              | 361.75      | 76.0                 | 25 32.9 49                | 2.78 3.75 5.5         |
| 12              | 412.7       | 106.7                | 34.3 44.6 72              | 3.83 5.04 7.4         |
| 13              | 363.85      | 75.7                 | 26.1 33.5 54              | 2.83 3.82 5.6         |
| 14              | 364.85      | 75.7                 | 24.8 31.8 52              | 2.7 3.6 5.3           |
| 15              | 415.8       | 58.7                 | 28.9 37 60                | 3.18 4.181 6.1        |
| 16              | 416.85      | 82.3                 | 32 41.5 67                | 3.56 4.69 6.9         |
| 17              | 318         | 51.0                 | 18.7 24.7 40              | 2.05 2.84 4.2         |
| 18              | 418.6       | 57.3                 | 29.6 38 62                | 3.26 4.29 6.3         |
| 19              | 419.8       | 56.7                 | 28.9 37.5 61              | 3.22 4.24 6.2         |
| 20              | 320.8       | 51.6                 | 17.9 23.7 38              | 1.96 2.73 4.0         |
| 21              | 421.9       | 108.1                | 32 41.3 67                | 3.55 4.67 6.5         |
| 22              | 322.9       | 86.7                 | 24.2 31.4 51              | 2.6 3.61 5.0          |
| 23              | 323.8       | 49.6                 | 20.3 26.3 43              | 2.18 3.02 4.2         |
| 24              | 425         | 57.9                 | 28.1 36.6 59              | 3.14 4.14 5.8         |
| 25              | 325.85      | 69.1                 | 21.1 27.9 45              | 2.31 3.21 4.5         |
| 26              | 376.85      | 75.7                 | 25.4 32.7 53              | 2.8 3.7 5.2           |
| 27              | 377.85      | 75.7                 | 26.1 33.5 38              | 2.83 3.82 5.3         |
| 28              | 378.95      | 76.4                 | 26.1 31.5 38              | 2.66 3.59 5.0         |
| 29              | 329.6       | 50.1                 | 19.5 25.5 28              | 2.11 2.93 4.1         |
| 30              | 331.1       | 88.0                 | 22.6 29.1 33              | 2.41 3.35 4.7         |

Figure 3. The outcomes of the screening analysis for the compressive and flexural strength.
Figure 4. Effect of cement and silica fume on the mechanical properties.

Table 4. Analysis of ANOVA for responses (Compressive and flexural strength).

| Source                  | F   | p-value | R² | Adj.R² | Remarks  |
|-------------------------|-----|---------|----|--------|----------|
| **Compressive Strength**|     |         |    |        |          |
| Model                   | 130.52 | < 0.0001 | 0.976 | 0.969 | significant |
| A-cement (Kg/M3)        | 730.33 | < 0.0001 |        |        |          |
| B-w/c ratio             | 0.21 | 0.6548 |    |        |          |
| C-F/C Ratio             | 22.30 | 0.0001 |    |        |          |
| D-silica (%)            | 144.52 | < 0.0001 |    |        |          |
| CD                      | 3.23 | 0.0862 |    |        |          |
| A²                      | 12.99 | 0.0016 |    |        |          |
| B²                      | 5.79 | 0.0250 |    |        |          |
| **Flexural Strength**   |     |         |    |        |          |
| Model                   | 192.27 | < 0.0001 | 0.956 | 0.951 | significant |
| A-cement (Kg/M3)        | 461.42 | < 0.0001 |    |        |          |
| C-F/C Ratio             | 15.13 | 0.0006 |    |        |          |
| D-silica (%)            | 100.27 | < 0.0001 |    |        |          |

The final regression models, in terms of the independent variables and responses, are expressed by the equations (1), and (2) for compressive and flexural strength, respectively.

**Compressive Strength (Mpa)** = +62.92428-0.41153* cement +101.39606* w/c
-6.56250* F/C+91.50000* silica-88.75000* F/C* silica+7.67742E-004*
cement²-128.06452* w/c² ...........................................................................(1)

**Flexural Strength (Mpa)** = -0.78841+0.013679* cement
-1.23833* F/C+6.37667* silica .................................................................(2)

6. Optimization of Preparation Parameters
An optimization process was implemented to determine the optimum value of cement, silica fume, W/C ratio and F/C ratio. Based on to the software optimization step, the preferred goal for each mix
design parameter was selected within the ranges required value. For compressive and flexural strength were set to greater than (30 Mpa) and 4.1 (Mpa) which they minimum requirement for design concrete pavement (SORB, 2003) [18]. Minimizing CO2 and cost were set to design Eco-friendly mixtures. It should be noted herein that the cost of each mixture was estimated by taking into account the cost of all the ingredients, for example, the cost of cement, sand, gravel, water etc. in one cubic meter of mixture. Same estimation was made regarding CO2 emission, where the emissions were adopted according to the previous studies that found estimated emissions to produce a certain material, for example, the CO2 emission resulted from manufacturing the steel fibers, cement etc.

According to the adopted procedure, the finalized cement, silica, F/A, and W/C are found. The results of the optimum value of variables and their response are listed in Table (5).

**Table 5.** The optimum variables with their responses.

| Responses            | Unit       | Optimal results | Desirability |
|----------------------|------------|-----------------|--------------|
| Cement               | Kg/M3      | 365             | 0.69         |
| Silica fume          | %          | 3.9             |              |
| Fine/course (F/C)    | ratio      | 0.3             |              |
| W/C                  | ratio      | 0.5             |              |
| Compressive Strength | Mpa        | 34.4            |              |
| Flexural Strength    | Mpa        | 4.1             |              |
| CO2 emission         | Kg CO$_2$e/m3 | 381            |              |
| Total Cost           | US$        | 72.7            |              |

### 7. Conclusions

In the present study, efforts were made to design Eco-friendly concrete mixtures taking into account lowering the costs and CO2 emissions through using low cement, where matching the Iraqi requirements regarding compressive and flexural strength. The following conclusions were drawn:

- It is found that cement amount and silica fume ratios are the higher factors affecting the mechanical properties flowed by fine-to-course aggregate and water-to-cementious ratio.
- Furthermore, good correlation between the adopted variables and mechanical properties (compressive and flexural strength) was found through statistical models, where the correlation coefficients R2 for all models were greater than 0.95.
- Optimal components to design concrete mixtures used in pavement that having compressive strength of (>30 Mpa) and flexural strength of (> 4.1 Mpa) are cement 365 kg/m3,silica fume 3.9%,F/C ratio of 0.3, and W/C ratio of 0.5.

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