Research on Compressive Strength of Manufactured Sand Concrete Based on Response Surface Methodology (RSM)

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Abstract: Traditional natural river sand is used as a fine aggregate for concrete, but due to the severe environmental situation in recent years, many places have asked for a ban or restriction on the extraction of river sand. This has resulted in an increasing demand for concrete using machine-made sand instead of natural sand. The estimation and prediction of the compressive strength of concrete is very important in civil engineering applications. In this investigation, a Box–Behnken test model was established to analyze the effect of stone powder (SP), pulverized fuel ash (PFA), and silica fume (SF) contents on the compressive strength of manufactured sand concrete using response surface methodology (RSM). A prediction model for the compressive strength of manufactured sand concrete was developed using multiple regression analysis with SP, PFA, and SF content as factors and compressive strength as the response value. In addition, the interaction of stone powder (SP), pulverized fuel ash (PFA), and silica fume (SF) content was analyzed according to the response surface and contour. The investigation showed that for single factors, SP had the greatest effect on the compressive strength of the manufactured sand concrete, with PFA having the second greatest effect, and SF the least; for the interactions, SP and PFA had the most significant effect, and the interaction between SP and SF and PFA and SF had the same effect on the compressive strength.

Keywords: manufactured sand concrete; RSM; SP; PFA; SF; compressive strength

1. Introduction

With the high speed of economic development and the increased investment in infrastructure in countries around the world, the amount of concrete used has increased dramatically [1,2]. Natural sand is a fundamental component of concrete, and with the increase in concrete consumption, more and more river sand is being mined. The widespread mining of river sand can have a negative impact on the surrounding environment; therefore, some rivers have now banned the mining of river sand. Manufactured sand is gradually replacing natural sand in building materials [3]. As shown in Figure 1, the consumption of aggregates and the proportion of manufactured sand used in China has increased from year to year over the last decade.

Manufactured sand is made from the crushing of sedimentary rocks and has some unique components not found in natural sand [4,5]. Manufactured sand is able to avoid the reactions between the active silica components of natural sand and the alkali metal hydroxides of cement. Numerous publications have shown that some of the properties of manufactured sand concrete are better than those of natural sand concrete [6–8]. Various mineral admixtures are an essential component to improve the performance of the manufactured sand concrete [9]. SP may induce hydride precipitation, which increases the strength of concrete by increasing the content of effective crystallization products [10]. PFA promotes deflocculation in the hydration of cement clinker to reduce water consumption and fills pores to prevent agglomeration between cement particles. The addition of
SF to concrete markedly improves the adhesion and cohesion of shotcrete and increases the sequential forming thickness. In addition, some publications have shown that the addition of SP, PFA, and SF to manufactured sand concrete can have a “superimposed effect” on each other, reducing the heat of hydration of the concrete while improving its mechanical properties [11–13]. Prakash [14], Beixing [15] et al. investigated the effect of SP content in manufactured sand on the mechanical properties of concrete. Skaropoulou [16], Schmidt [17] et al. showed that the SP content of manufactured sand has an important influence on the durability of concrete. Wentao et al. [18] investigated the effects of PFA alone, SP alone, and a combination of PFA and SP on the workability and strength of manufactured sand concrete. Heng et al. [19] modified the concrete by incorporating PFA into the manufactured sand. His design for shotcrete, with a PFA admixture of 40% and a water-cement ratio of 0.37, reduced the water consumption while reducing the rebound rate of the shotcrete. Jain [20] found that the addition of marble powder reduced the strength of ordinary Portland cement. After curing the concrete with 20% marble powder for 28 days, a maximum compressive strength of 54.5 MPa was achieved. Currently, most publications report the effect of a single admixture of SP, PFA, and SF or both on the strength of manufactured sand concrete. However, no investigation of the combined effect of the three on compressive strength has been reported.

![Figure 1. Aggregate consumption and proportion of manufactured sand in China.](image)

Response surface methodology (RSM) is a statistical method for solving multivariate problems that enables experiments to be conducted using rational experimental design methods with multivariate quadratic equations to be fitted as a function of the relationship between factors and response values. The Box–Behnken experimental design in RSM has been widely used in engineering applications since it was proposed [21], and research on admixtures and concrete has recently become a hot topic. Zhang et al. [22] applied RSM to the design of a recycled aggregate permeable concrete mix and found a suitable combination of aggregate gradation and admixture mix. Natalia et al. [23] used the two-level central composite design in RSM to optimize the ratio of water-to-binder, PFA-to-binder and iron oxide nanoparticles-to-binder for Portland cement permeable concrete. Rajesh and Kumar [24] used Box–Behnken design optimization with RSM to obtain concrete with good hardening and functional properties. Khudhair et al. [25] used RSM to determine a model for predicting the compressive strength of high-performance concrete formulated by a high water reducing and setting accelerating superplasticizer as a function of the proportion of the constituents used.
A review of the literature reveals that the use of admixtures in manufactured sand concrete is common. The effect of various admixtures on the properties of manufactured sand concrete is an issue that needs to be addressed. Among these issues, the estimation and prediction of the compressive strength of manufactured sand is very important in civil engineering applications. At the same time, the RSM is able to fit the relationship between the factors and the response values obtained. Therefore, in this investigation, the Box–Behnken design based on RSM used SP, PFA, and SF admixtures as factors and compressive strength as response values to study the effect of the three admixtures on compressive strength. A multivariate predictive regression model for each factor was developed to analyze the magnitude of the effect of the factors. This investigation can provide an experimental basis and theoretical guidance for the design of manufactured sand concrete.

2. Experimental Materials and Methods

2.1. Experimental Materials

2.1.1. Cement and Water

In this work, ordinary silicate PO42.5 cement produced by Shandong Shanshui Cement Group Co., Ltd. (Rizhao, Shandong) was used for the experiments and the quality was in accordance with the GB175-2020 standard (General Purpose Silicate Cement in China) and ASTM C150 (Standard Specification for Portland Cement). The chemical composition of the cement is shown in Table 1. The specific surface area of the cement is 338 m²/kg, the loss on burning is 4.54%, the initial setting time is greater than 45 min, and the final setting time is less than 600 min.

Table 1. Chemical composition of concrete.

| Constituents | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO  | MgO | SO₃ |
|--------------|------|-------|-------|------|-----|-----|
| Content (wt%)| 20.81| 4.54  | 3.15  | 64.22| 2   | 2.5 |

All water used for the experiments was from tap water, in accordance with the requirements of JGJ63-2006, Standard of Water for Concrete.

2.1.2. Manufactured Sand and Coarse Aggregates

In this work, all of the manufactured sand was obtained from the first phase of the Qingdao underground railway, Line 6, project in Shandong Province. The underground railway construction was carried out by blasting and the resulting stones were large and needed to be crushed and sieved before they could be used. In this work, a jaw crusher was used to crush the blocks and screen the manufactured sand according to the gradation as shown in Figure 2.

![Figure 2. Manufactured sand and gravel gradation.](image-url)
The coarse aggregate was made of durable gravel with a particle size of 5–10 mm, in accordance with GB50086-2015 Technical Specification for Anchor-Shotcrete Support. As shown in Figure 2, in this work both, the manufactured sand and gravel aggregate grade lines are located between the upper and lower lines of the shotcrete technical standard grade.

2.1.3. Stone Powder (SP)

The SP content within a reasonable range can be give concrete good workability; beyond this range, SP will have a negative impact. If the water-SP ratio is too large, it is easy to produce segregation and water secretion. For concrete with a large water to cement ratio, SP can be relied upon to reduce the water-SP ratio to improve cohesion and enhance water retention and reduce segregation and water secretion. In addition, if the SP content is too high, it will reduce the flowability of the concrete.

The SP in this work was obtained by sieving the crushed machine-made sand with a particle size of less than <0.075 mm. Three levels of SP content were set at 5%, 10%, and 15% of the cement mass, respectively.

2.1.4. Pulverized Fuel Ash (PFA)

PFA can act as an activator and filler, allowing the structural density of the concrete to increase. The morphological and micro-aggregate filling effects of PFA can improve the flowability of concrete mixtures in the early stages of concrete mix formation. The PFAs in the experiments in this work were all supplied by Class F, produced by Henan Hengyuan New Materials Co. (Zhengzhou, China) The chemical composition of PFA is shown in Table 2. The fineness, water requirement ratio, burn vector, and water content are 8.7%, 91%, 2.8%, and 0.2%, respectively, which meet the requirements of Grade I PFA for the relevant parameter index. The PFA content in this work was set at three levels of 10%, 15%, and 20% of the cement mass.

Table 2. Chemical composition of PFA.

| Constituents | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | TiO₂ | K₂O | MgO |
|--------------|------|-------|-------|-----|------|-----|-----|
| Content (wt%)| 32.61| 24.54 | 3.45  | 4.42| 0.93 | 0.84| 0.56|

2.1.5. Silicon Fume (SF)

If the content of SF in the concrete is too small, the concrete performance is not much improved, but if the content is too much, the concrete is too sticky and hard to form, and the dry shrinkage deformation is large, showing poor frost resistance. The SF in this paper is produced by Henan Hengyuan New Materials Co. and its chemical composition is shown in Table 3. The density is 2.4 g/cm³ and the specific surface area is 75,000 m²/kg. Three levels of SF are set, 2.5%, 5%, and 7.5% of the cement mass, respectively.

Table 3. Chemical composition of SP.

| Constituents | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | SO₃ | K₂O | MgO | Na₂O |
|--------------|------|-------|-------|-----|-----|-----|-----|------|
| Content (wt%)| 92.5 | 0.2   | 0.6   | 0.12| 0.44| 1.52| 0.15| 0.37 |

2.2. Experimental Methods

2.2.1. Concrete Mixing Ratio

The water to cement ratio for the concrete in this work is 0.5, where the cement, gravel, manufactured sand, and water are configured in the ratio of 1:1.5:2.25:0.5. SP, PFA, and SF as a percentage of the mass of the cement. According to the Box–Behnken experiment design in the RSM, a total of 17 mix ratios are required at different contents, of which the SP, PFA, and SF contents are shown in Table 4 as a percentage of the cement mass. The test results are the average of the compressive strength of the three blocks.
Table 4. SP, PFA, and SF contents.

| No. | SP  | PFA | SF  |
|-----|-----|-----|-----|
| 1   | 5%  | 10% | 5%  |
| 2   | 15% | 10% | 5%  |
| 3   | 5%  | 20% | 5%  |
| 4   | 15% | 20% | 5%  |
| 5   | 5%  | 15% | 2.5%|
| 6   | 15% | 15% | 2.5%|
| 7   | 5%  | 15% | 7.5%|
| 8   | 15% | 15% | 7.5%|
| 9   | 10% | 10% | 2.5%|
| 10  | 10% | 20% | 2.5%|
| 11  | 10% | 10% | 7.5%|
| 12  | 10% | 20% | 7.5%|
| 13  | 10% | 15% | 5%  |
| 14  | 10% | 15% | 5%  |
| 15  | 10% | 15% | 5%  |
| 16  | 10% | 15% | 5%  |
| 17  | 10% | 15% | 5%  |

2.2.2. Concrete Block Making

Concrete blocks are made in accordance with the requirements of the Standard for Test Methods of Mechanical Properties on Ordinary Concrete GB/T50081-2016 standard for the production of specimen dimensions, and the mold size is $100 \times 100 \times 100$ mm. The concrete was prepared in accordance with the concrete ratios in Section 2.2.1 and the additive content in Table 4. The gravel, manufactured sand, and cement are first mixed in a concrete mixer for 1 min, after which water and other admixtures are added and mixed for an additional 3 min. The mixed concrete was poured into the molds and placed on a vibrating table for a period of 4 min. It should be noted that the vibration process resulted in a reduction of concrete in the molds; therefore, concrete had to be continuously added to the molds until it overflowed. Finally, the concrete was scraped off the molds, cured at room temperature for 24 h, and then demolded. After demolding, the concrete blocks were cured for 28 days according to the standards [26]. The concrete block-making process is shown in Figure 3.

Figure 3. Concrete block-making process.

2.2.3. Compressive Strength Test

The test of compressive strength is performed by a digital display type pressure tester (DYE-2000); the test content is evaluated for uniaxial compressive strength. The test procedure is shown in Figure 4. The cubic block is placed on the base of the pressure testing machine and the pressure is transmitted downwards to the concrete block through
the upper plate. The loading speed of the force is hydraulically controlled at around 0.8 mm/min. The pressure tester records and outputs the maximum pressure value as the compressive strength [27].

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Figure 4. The test of compressive strength.

3. Results and Discussion

3.1. Box–Behnken Experiment Design and Significance Test

3.1.1. Box–Behnken Experiment Design

The Box–Behnken test factors and levels are shown in Table 5, using the uniaxial compressive strength values as the response values and the SP content ($X_1$), PFA content ($X_2$), and SF content ($X_3$) as the investigating factors. The test results and analysis are shown in Table 6.

Table 5. Factors and levels of Box–Behnken experiments.

| Factors                  | −1 | 0 | 1 |
|--------------------------|----|---|---|
| $X_1$ (SP content)       | 5% | 10%| 15%|
| $X_2$ (PFA content)      | 10%| 15%| 20%|
| $X_3$ (SF content)       | 2.5%| 5% | 7.5%|

Table 6. Results and analysis of Box–Behnken experiments.

| No. | $X_1$ | $X_2$ | $X_3$ | Y/Compressive Strength (MPa) |
|-----|-------|-------|-------|-----------------------------|
| 1   | 5%    | 10%   | 5%    | 43                          |
| 2   | 15%   | 10%   | 5%    | 45                          |
| 3   | 5%    | 20%   | 5%    | 46                          |
| 4   | 15%   | 20%   | 5%    | 44                          |
| 5   | 5%    | 15%   | 2.5%  | 46                          |
| 6   | 15%   | 15%   | 2.5%  | 41                          |
| 7   | 5%    | 15%   | 7.5%  | 46                          |
| 8   | 15%   | 15%   | 7.5%  | 44                          |
| 9   | 10%   | 10%   | 2.5%  | 43                          |
| 10  | 10%   | 20%   | 2.5%  | 38                          |
| 11  | 10%   | 10%   | 7.5%  | 41                          |
| 12  | 10%   | 20%   | 7.5%  | 39                          |
| 13  | 10%   | 15%   | 5%    | 46                          |
| 14  | 10%   | 15%   | 5%    | 48                          |
| 15  | 10%   | 15%   | 5%    | 49                          |
| 16  | 10%   | 15%   | 5%    | 47                          |
| 17  | 10%   | 15%   | 5%    | 48                          |

The least squares method was used to fit the experimental data, and a regression model was developed as follows:
\[ Y = 47.6 - 0.87X_1 - 0.62X_2 + 0.25X_3 - X_1X_2 + 0.75X_1X_3 + 0.75X_2X_3 + 0.45X_1^2 - 3.55X_2^2 - 3.8X_3^2 \]  
\[ R^2 = 0.85 \]  

3.1.2. Significance Test

The standard quadratic regression equation (Equation (1)) was analyzed for variance, and the results are shown in Table 7. The model was tested for significance using ANOVA. The significance level was set at 0.05, i.e., when the \( p \)-value was less than 0.05, the indicator was considered significant; when the \( p \)-value was greater than 0.05, the indicator was considered insignificant. Table 7 shows that the \( p \)-value of the quadratic regression model for compressive strength is less than 0.05, and the multivariate correlation coefficient \( R^2 \) is 0.85. This indicates that the regression equation approximates the true surface well, and the model can accurately predict the compressive strength of the manufactured sand concrete.

| Source          | Squares | df | Square  | Value | Prob > F  |            |
|-----------------|---------|----|---------|-------|-----------|------------|
| Model           | 138.43  | 9  | 15.38   | 4.59  | 0.0285    | significant|
| X1-SP           | 6.12    | 1  | 6.12    | 1.83  | 0.2184    |
| X2-PFA          | 3.12    | 1  | 3.12    | 0.93  | 0.3663    |
| X3-SF           | 0.50    | 1  | 0.50    | 0.15  | 0.7107    |
| X1 X2           | 4.00    | 1  | 4.00    | 1.19  | 0.3107    |
| X1 X3           | 2.25    | 1  | 2.25    | 0.67  | 0.4395    |
| X2 X3           | 2.25    | 1  | 2.25    | 0.67  | 0.4395    |
| X1\(^2\)        | 0.85    | 1  | 0.85    | 0.25  | 0.6294    |
| X2\(^2\)        | 53.06   | 1  | 53.06   | 15.84 | 0.0053    |
| X3\(^2\)        | 60.80   | 1  | 60.80   | 18.15 | 0.0037    |
| Residual        | 23.45   | 7  | 3.35    |       |           |            |
| Lack of Fit     | 18.25   | 3  | 6.08    | 4.68  | 0.0851    | not significant|
| Pure Error      | 5.20    | 4  | 1.30    |       |           |            |
| Cor Total       | 161.88  | 16 |         |       |           |            |

As shown in Table 7, the squares for SP, PFA, and SF were 6.12, 3.12, and 0.50, respectively, which shows a significant effect on the compressive strength of the single factors: SP has the greatest effect on the compressive strength of the concrete, PFA has the second greatest effect, and SF has the least effect. Similarly for the interaction, SP and PFA had the most significant effect on the compressive strength of the manufactured sand concrete, and the interaction between SP and SF and PFA and SF had the same effect on the compressive strength.

3.2. Prediction Model Validation

The reliability of the prediction model is verified through experimentation. Four sets of concrete blocks with different SP, PFA, and SF contents were created to measure the uniaxial compressive strength and were then compared with the prediction model. The content of SP, PFA, and SF used for the model validation experiments is shown in Table 8. The block-making process and compressive strength testing of the manufactured sand concrete blocks for the model validation experiments were the same as the methods previously mentioned in Section 2.2. The compressive strength experiments, predicted values, and relative errors are shown in Figure 5.
Table 8. The SP, PFA, and AF content of the validation experiments.

| No. | SP  | PFA | SF  |
|-----|-----|-----|-----|
| 1   | 7%  | 12% | 2.5%|
| 2   | 10% | 15% | 6%  |
| 3   | 12% | 17% | 2.5%|
| 4   | 15% | 20% | 7%  |

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As can be seen from Figure 5, the relative error between the experimental and predicted values is less than 10%; therefore, the predictive model for the compressive strength of the manufactured sand concrete developed in this investigation can be considered to be credible.

3.3. Response Surface and Contour Analysis

The effect of the interaction between SP, PFA, and SF on the compressive strength was analyzed using response surface and contour analysis based on the regression equation for the compressive strength of the manufactured sand concrete. Another factor was controlled for at an intermediate level when discussing the pattern of interaction effects on compressive strength. The intermediate levels of SP, PFA, and SF content in this work were 10%, 15%, and 5% of the cement mass, respectively, as described in the previous section.

3.3.1. Effect of SP and PFA Interaction

Keeping the SF at an intermediate level, the response surface and contour in SP-PFA are shown in Figure 6. As can be seen in Figure 6a, the entire response surface takes on an “arch” shape when the SF is 5%. This indicates that the compressive strength tends to increase and then decrease as the SP and PFA content increases, with a maximum value existing. As can be seen from the contour lines in Figure 6b, the contour lines in the upper right corner of the picture are more densely distributed, which indicates that when the SP content and the PFA content are high, the change in PFA content has a greater effect on the fluctuation of the compressive strength. It is worth noting that the higher and lower contents described here correspond to the ranges set in this study. In the case of PFA, for example, the content in this work is between 10% and 20% by mass of cement, so this is the higher PFA content described to indicate a content close to, but not exceeding, 20%. The same rule is followed in the subsequent discussion.
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Figure 6. Response surface and contour in SP-PFA. (a) Response surface. (b) Contour.

3.3.2. Effect of SP and SF Interaction

Similarly, keeping the PFA at an intermediate level, the response surface and contour in SP-SF are shown in Figure 7. The response surfaces of Figures 6a and 7a both have an “arch” shape. Unlike Figures 6b and 7b has a higher degree of symmetry above and below the contour lines. In addition, as can be seen from the denseness of the contours in Figure 7b that the change in SF content has a greater effect on the fluctuation of the compressive strength when the SP content is high and the amount of SF is low. This means that when the PFA content is 15% of the cement mass and the SF content is less than 3.5% or greater than 6.5%, the effect of the change in SF content on the compressive strength fluctuates more than if the SF content is greater than 3.5–6.5%.
Similarly, keeping the PFA at an intermediate level, the response surface and contour in SP-SF are shown in Figure 7. The response surfaces of Figures 6a and 7a both have an "arch" shape. Unlike Figure 6b, Figure 7b has a higher degree of symmetry above and below the contour lines. In addition, as can be seen from the denseness of the contours in Figure 7b that the change in SF content has a greater effect on the fluctuation of the compressive strength when the SP content is high and the amount of SF is low. This means that when the PFA content is 15% of the cement mass and the SF content is less than 3.5% or greater than 6.5%, the effect of the change in SF content on the compressive strength fluctuates more than if the SF content is greater than 3.5–6.5%.

Figure 7. Response surface and contour in SP-SF. (a) Response surface. (b) Contour.

3.3.3. Effect of PFA and SF Interaction

When the SP is at an intermediate level, the response surface and contour in PFA-SF are shown in Figure 8. As can be seen from Figure 8a, the highest values exist across the response surface and are in the center, corresponding to a compressive strength of around 48 MPa for the manufactured sand concrete block. This indicates that in this study, the manufactured sand concrete exhibited a high compressive strength when the SP, PFA, and SF contents were all at intermediate levels. As can be seen in Figure 8b, the contours are centrosymmetric and equally spaced between the surrounding contours. This shows that equal variations in PFA and SF content have the same fluctuating effect on the compressive strength when the SP is at an intermediate level. In addition, the top leftmost corner of the contour in Figure 8b shows a compressive strength of less than 42 MPa, which is due to the high SF content and the low PFA content.
that equal variations in PFA and SF content have the same fluctuating effect on the compressive strength when the SP is at an intermediate level. In addition, the top leftmost corner of the contour in Figure 8b shows a compressive strength of less than 42 MPa, which is due to the high SF content and the low PFA content.

Figure 8. Response surface and contour in SFA-SF. (a) Response surface. (b) Contour.

4. Conclusions

An investigation of the compressive strength of manufactured sand concrete containing stone powder (SP), pulverized fuel ash (PFA), and silicon fume (SF) using the Box–Behnken experiment design in the response surface method (RSM) provides the following conclusions:

(1) A prediction model of the compressive strength of manufactured sand concrete with SP, PFA, and SF content was developed using multiple regression analysis with SP, PFA, and SF content as factors and compressive strength as the response value; the multiple correlation coefficient $R^2$ of the prediction model was 0.85. The prediction model for the compressive strength of concrete using manufactured sand was validated experimentally, and the validation results showed that the prediction model was credible, with a relative error of less than 10% between the experimental and predicted values.

(2) The statistical values of the single factors were analyzed and the degree of significance of the single factors on the compressive strength showed that SP content had the greatest effect on the compressive strength of the manufactured sand concrete, with PFA having the next greatest effect, and SF having the least effect. For the interactions, SP and PFA content had the most significant effect on the compressive strength of the manufactured sand concrete, while the interactions between SP and SF and PFA and SF had the same effect on the compressive strength.
Response surface and contour analyses were carried out where the SP, PFA, and SF contents were kept at moderate levels (10%, 15%, and 5% of cement mass, respectively). The results show that the compressive strength tends to increase and then decrease with increasing SF and PFA content, with a maximum value. The maximum compressive strength of the concrete was found when the SP, PFA, and SF contents were all at intermediate levels.

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Abbreviations

| Designation | Explanation |
|-------------|-------------|
| RSM         | response surface method |
| SP          | stone powder |
| PFA         | pulverized fuel ash |
| SF          | silicon fume |

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