



Article

Study on the Characteristics of Composite Recycled Aggregate Concrete Based on Box–Behnken Design Response Surface Model

Haizhou Li ^{1,2,3}, Lu Zhang ^{2,3,4,*}, Jianping Liu ⁴, Fujiao Chu ¹  and Yifan Tian ⁴

¹ School of Resources and Environmental Engineering, Shandong University of Technology, Zibo 255000, China; lihaizhou@sdut.edu.cn (H.L.)

² Key Laboratory for Liquid-Solid Structural Evolution & Processing of Materials of Ministry of Education, Shandong University, Jinan 250061, China

³ Shantian Abrasive Co., Ltd., Linyi 276700, China

⁴ School of Civil Engineering and Geomatics, Shandong University of Technology, Zibo 255000, China; liujp@sdut.edu.cn (J.L.); 17306321198@163.com (Y.T.)

* Correspondence: zlu@sdut.edu.cn

Abstract: This study investigates the influence of recycled fine aggregates (RFA) and waste concrete powder (WCP) on the compressive strength of concrete. The response surface methodology is employed, considering three factors: the content of WCP, the water–cement ratio, and the replacement ratio of recycled fine aggregates. Compressive tests are conducted at different ages (3 days, 28 days, and 90 days). A statistical approach is used to establish a response surface model for compressive strength and to verify its fitting with experimental results. By combining qualitative and quantitative analyses, including morphological analysis of SEM images, stratified binarization statistics, and fractal dimension calculations, the mechanisms of the effects of singly and doubly mixed RFA and WCP on the compressive strength of concrete are analyzed. The results show that an increase in the content of WCP from 5% to 15% gradually improves the compressive strength of the concrete. The water–cement ratio significantly affects the compressive strength, with an optimal ratio of 0.43. Replacement with less than 33% fine aggregates does not significantly reduce the compressive strength of the concrete. The concrete specimens with singly mixed fine aggregates exhibit the largest pore area after stratified grayscale binarization, while those with doubly mixed aggregates have the largest area of hydrated calcium silicate. Fractal analysis of the binarized images confirms a positive correlation between the fractal dimension of hydrated calcium silicate and compressive strength and a negative correlation between the fractal dimension of pores and compressive strength.

Keywords: waste concrete powder (WCP); recycled fine aggregate (RFA); compressive strength; Box–Behnken design; fractal dimension



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1. Introduction

The global demolition of retired concrete structures generates a significant amount of construction waste each year, posing a severe threat to the human living environment [1]. At the same time, the construction of new concrete buildings requires a considerable amount of natural sand and gravel as aggregates, leading to an increasing demand for non-renewable resources [2,3]. These two prominent issues in the construction industry converge at a common point, where the crushing and grading treatment of old concrete buildings enables the matching of corresponding levels of waste particles to replace natural aggregates. This approach, which involves the low-cost and high-efficiency recycling of construction waste, serves as an effective method for addressing environmental pollution and preventing resource depletion [4].

According to different sources, construction waste can be divided into waste concrete, waste brick and tile, old mortar, and waste residue. Statistics show that concrete waste

accounts for 65% of all construction waste [5]. Waste concrete is usually divided into two types after crushing: the first type is made of particles with a diameter greater than 4.75 mm, accounting for about 30–40% of the total mass of waste concrete. Particles of this diameter usually comprise the natural aggregate that encapsulates the old mortar. After simple treatment, the waste concrete has high strength and good quality and can replace the genuine article [6]. The second category is made of particles with a particle size of less than 4.75 mm, which account for about 60% to 70% of the total mass of discarded concrete. It may contain natural sand, mortar powder, and unhydrated mineral particles, and the composition is very complex. In this kind of waste concrete, particles with particle grading between 0.075 mm and 4.75 mm can replace fine aggregates. It is worth noting that the waste concrete crushing process also produces particles with a particle size below 0.075 mm, usually called waste concrete powder (WCP) [7]. The total weight of the regenerated micro-powder is about 20–30% of the second type of waste concrete [8]. Since the recycled micro-powder may increase the mixed concrete's water requirement, the fluidity, mechanical properties, and even durability of the concrete solid are affected [9,10]. Therefore, code stipulates that the recycled fine aggregate crushed by waste concrete must remove particles with a particle size below 75 μm . The process of sieving to remove recycled micro-powder increases the cost of construction waste treatment, and there are technical difficulties [11]. Therefore, recycled WCP is a bottleneck problem in the field of concrete waste.

Scholars have primarily focused their research on the preparation of recycled coarse and fine aggregates in the context of utilizing waste concrete, and significant progress has been made in this area [12,13]. However, research on WCP is still in the exploratory stage, with overall utilization rates remaining relatively low. The WCP produced from crushed waste concrete consists primarily of cement, along with SiO_2 generated from the crushing of coarse and fine aggregates [14,15]. Relevant studies have shown that WCP can be appropriately incorporated into concrete as a mineral admixture, serving as a supplementary cementitious material to replace a portion of cement. Research on the performance and application of WCP demonstrates that it exhibits a certain level of hydration activity and can be blended into raw materials as an auxiliary cementitious material. The reaction between WCP and the calcium hydroxide produced by the cementitious material system effectively promotes cement hydration [16], leading to improvements in pore structure and significant enhancements in the mechanical and durability properties of concrete [17,18]. However, the WCP particles produced by conventional crushing processes tend to be larger and exhibit lower reactivity when used as auxiliary cementitious materials [19]. To unleash their full reactivity, the WCP must undergo processes such as calcination or thorough grinding, which consume significant energy and generate a substantial amount of pollution gases. The emissions of large quantities of CO_2 from the grinding process are considered a significant contributor to the current global greenhouse effect, rendering such treatment methods unable to achieve the original intention of harmless treatment of construction waste [20,21].

Based on the current research status mentioned above, the utilization of waste particles with a diameter smaller than 4.75 mm remains a bottleneck in the harmless disposal of concrete. There are several factors that can influence the compressive strength of concrete with recycled fine aggregates. The most important factors include the content of WCP, the water–cement ratio, and the content of recycled fine aggregates. Considering all these factors and their interactions requires a significant number of experiments to be conducted. Moreover, experimental errors can affect the accuracy of the conclusions. To overcome these issues, experimental design methods are needed. In some studies, advanced design methods have been used for the optimal mixture design of concrete materials. For example, Kumar R utilized response surface methodology to design structural-grade lightweight cellular concrete containing micro-fine stone sludge [22]. Sharaky I A constructed a cube strength equation for concrete using Central Composite and Box–Behnken designs, accurately predicting the effects of steel fiber content, high kaolin clay content, and curing time on compressive strength [23]. Shaheen N optimized the formulation of a microorganism

cementitious composite using the Taguchi approach of experimental design, considering factors such as water–cement ratio, type of cement, and effective microorganism technology [24]. Zhang Q optimized the mix proportion of recycled aggregate pervious concrete using response surface methodology and established the response of void content for different gradations of recycled aggregates using a simplex–centroid design [25]. To address the two major issues of fully utilizing fine aggregates and harmless disposal of WCP, this study replaces the fine aggregates with particles ranging from 0.075 mm to 4.75 mm, which are obtained by crushing waste concrete. The WCP below 0.075 mm are used as inert fillers to prepare recycled aggregate concrete. The Box–Behnken method is employed to design and assess the effects of three factors, namely the content of WCP, water–cement ratio, and content of recycled fine aggregates, on the compressive strength of concrete. The interactions among these three factors are evaluated. Using the aforementioned factors as independent variables, response models for the compressive strength of concrete at 3 days, 28 days, and 90 days are constructed. The models are evaluated and validated using variance analysis and R^2 . By plotting three-dimensional response surfaces, the optimal mixture conditions for achieving the highest strength in recycled concrete are determined. Finally, the changes in concrete strength due to the addition of WCP and recycled fine aggregates are quantitatively described from a microscopic perspective through the characterization of morphological features and calculation of fractal dimensions based on SEM micrographs. This reveals the mechanisms through which each factor affects the strength. These findings provide a basis for further enhancing the utilization efficiency of recycled micro-powder, as well as expanding its functionality and application scenarios.

2. Experimental Section

2.1. Raw Materials

The experimental cement material used in the study was 42.5-grade Portland cement, with a clinker content of 88.7% and a density of 2980 kg/m^3 , in accordance with Chinese standard GB175-2007 [26].

The natural coarse aggregate (NCA) was crushed limestone, with a continuous particle size ranging from 5 mm to 20 mm. The testing was conducted following the Chinese standard “Construction Use Gravel and Crushed Stone” (GB/T 14685-2011) [27].

The natural fine aggregate (NFA) was river sand, with a fineness modulus of 2.6, falling within the category of medium sand.

The recycled fine aggregate (RFA) was obtained by crushing laboratory waste concrete specimens, which were originally made with C45 concrete blocks. After crushing, recycled fine aggregate with the same particle size distribution as the natural fine aggregate was separated using a sieve shaker. The aggregate grading can be seen in Figure 1.

According to the relevant provisions of the standard “Quality and Testing Methods for Sands and Stones Used in Ordinary Concrete” JGJ 52-2006 [28], the physical properties of each aggregate were measured, including the water absorption rate, apparent density, and moisture content of the recycled coarse and fine aggregates, as shown in Table 1.

Table 1. Basic properties of aggregate.

Type	Performance Density (kg/m^3)	Loose Packing Density (kg/m^3)	Crushing Value Index (%)	Princess (%)	Water Absorption Rate at 24 h (%)	Moisture Content (%)
NCA	2670	1566	18.2	18	1.1	1
NFA	2530	1506	13.7	7	1.4	1.77
RFA	2330	1280	27	5	15.4	5.8

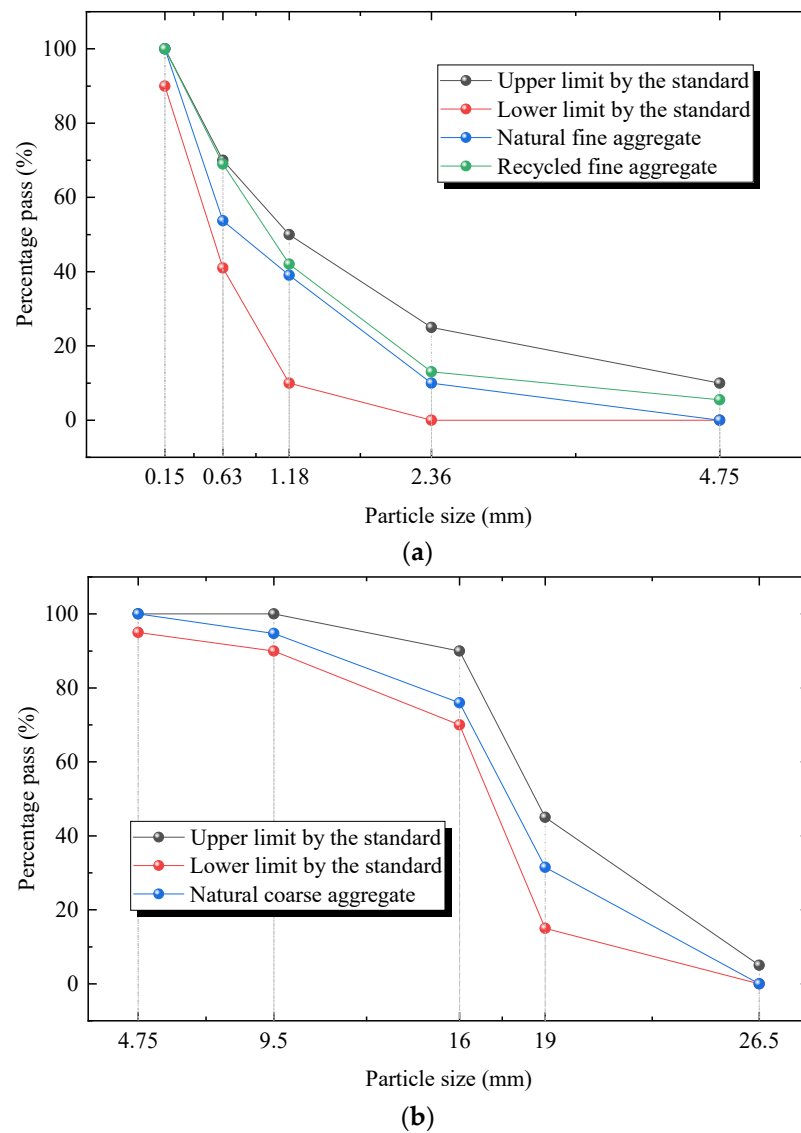


Figure 1. Comparison of the particle size distributions of aggregate. (a) Fine aggregate. (b) Coarse aggregate.

Admixture was performed with high-performance polycarboxylic acid-series water-reducing agent (the amount is 0.5% of the amount of cement), the purpose of which was to ensure the workability of mixing concrete. The indexes of the water-reducing agent are shown in Table 2.

Table 2. Performance index of water-reducing agent.

Water-Reducing Rate (%)	Air Content (%)	pH Level	Density (kg/m ³)	Water-Reducing Rate (%)
30	2.4	7.9	1053	24

Mixing with water was conducted using tap water, in line with the JGJ 63-2006 standard requirements [29].

2.2. WCP

2.2.1. Screening Test

The discarded concrete was broken by impact and then subjected to secondary crushing in a jaw crusher. After electric sieving, the mass was measured. The results showed

that the mass of particles with a diameter less than 0.075 mm accounted for 11.3% of the mass of particles with a diameter below 4.75 mm. These particles can be considered as WCP, as depicted in Figure 2. WCP exhibits a micro-aggregate effect and may also possess reactivity, which can influence the strength of freshly mixed concrete. The particle size distribution of the WCP was analyzed using a Mastersizer 2000 in this study. The particle sizes of the WCP mainly ranged from 0.25 μm to 200 μm , with $d(0.1)$ at 1.172 μm , $d(0.5)$ at 26.136 μm , and $d(0.9)$ at 74.218 μm . The density of the prepared WCP was 2570 kg/m^3 . The high specific surface area of the WCP may result in a higher water demand and decrease the flowability of freshly mixed cementitious materials.



Figure 2. Morphology of regenerated micro-powder.

2.2.2. Oxide Content

To investigate the oxide content in the raw material of WCP, a semi-quantitative (qualitative) analysis of the samples was performed using X-ray spectroscopy. A loose sample of 50 mg of WCP was taken and dried at a constant temperature of 60% °C for 48 h in a vacuum drying oven. The oxide content was measured using an X-ray fluorescence spectrometer, model Brook S2 RANGER. The results are presented in Table 3.

Table 3. X-ray spectrum analysis table of WCP (%).

Element	CaO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	TiO ₂	ZrO ₂	LOI
Content	43.73	26.55	8.19	13.18	4.99	0.75	2.21	0.05	0.03	0.03	0.29

As shown in the Table 3, the main components of the WCP were CaO, SiO₂, and Al₂O₃, which are very similar to the main components of cement. During the process of crushing waste concrete, natural aggregates are rarely crushed into WCP, while cement paste is more easily crushed into WCP. The high content of SiO₂ and Al₂O₃ gives the WCP a potential pozzolanic effect, which is consistent with the findings of the study in reference [30].

2.3. Experimental Design and Methods

In previous studies, the impact of variations in a single factor on compressive strength was often considered. However, in reality, changes in one factor can simultaneously induce changes in other factors, and the interaction effects may influence the indicators of compressive strength. This is known as “response effect”. Based on this, this study utilizes the compressive strength indicators at 3 d, 28 d, and 90 d to evaluate the short-, middle-, and long-term strength of concrete. The response surface methodology was

employed to analyze the significant effects of both single and interaction factors on the evaluation indicators.

2.3.1. Basic Mixing Ratio

According to the design code JGJ55-2011 “Code for Design of Concrete Mix Proportions” [31], the cement dosage was set at 406 kg/m^3 . All coarse aggregates were natural aggregates with a dosage of 1290 kg/m^3 . The total amount of fine aggregates was 695 kg/m^3 , with the recycled fine aggregates replacing the natural fine aggregates in equivalent mass. The WCP was added separately based on a percentage of the mass of the fine aggregates. The dosage of the water-reducing agent was 4.87 kg/m^3 .

The water absorption rate of the RFA was significantly higher than that of the corresponding natural aggregates. In this study, the water absorption rate of the RFA used was 11 times that of the NFA after 24 h. The 70% additional water method was adopted, where the calculation was based on the difference between 70% of the water absorption capacity of the RFA (product of water absorption rate and mass) and the moisture content of the RFA (product of moisture content and mass). This difference was added as additional water to the freshly mixed concrete.

2.3.2. BBD Trial Protocol

The Box–Behnken design (BBD) used in response surface analysis are a type of 3-level experimental design method. The experiment adopts an incomplete block design, where the designed experiment does not include all possible combinations of the three factors. However, each factor has at least one opportunity to run at the same time with each level of the other factors, forming an experimental plan. BBD can effectively utilize each experimental unit without generating excessive experimental groups [32]. Figure 3 represents a schematic diagram of factor-level coding in BBD.

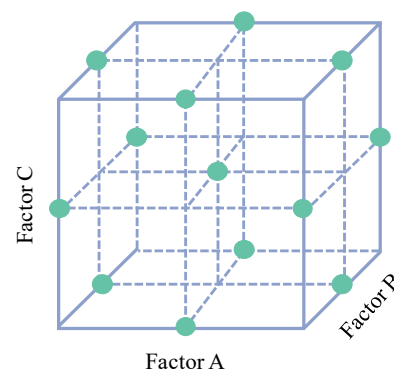


Figure 3. Factor BBD encoding factor levels.

As shown in Figure 3, the three selected factors in the experiment can be combined to form a cube. When conducting optimal combinations using BBD, the endpoints of the cube are not included. All selected points can only be located on a spherical surface or at the center of the sphere. Therefore, when an experiment requires the design of multiple factors with different levels, and conducting endpoint experiments is either cost-prohibitive or physically unfeasible, the use of BBD design is highly advantageous [22]. The optimization design of concrete mix proportions falls under the category of experimental design with interactions among multiple factors at different levels. Parallel experiments cannot accurately identify the endpoints, making BBD design suitable in this case. The variable factors chosen were the dosage of WCP, water–cement ratio, and replacement rate of RFA, with the levels of these factors listed in Table 4.

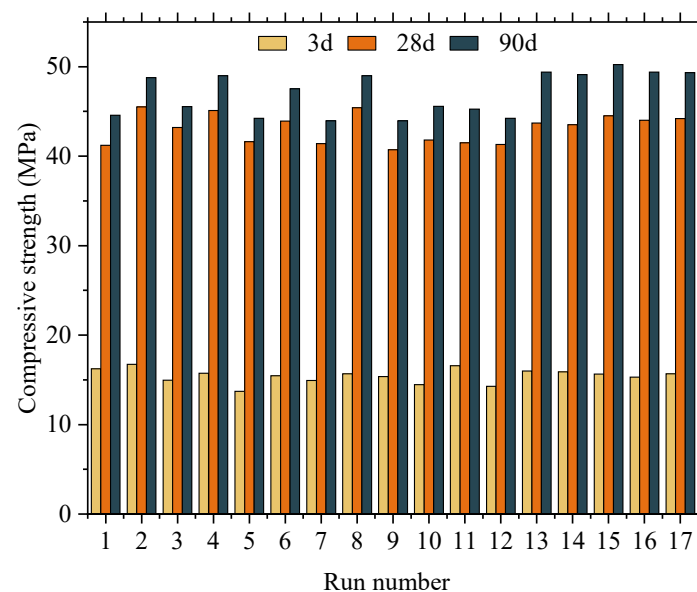
Table 4. Table of BBD factor levels.

Number	Variable Factors	Level		
A	Percentage of WCP (%)	5	10	15
B	Water–cement ratio	0.35	0.4	0.45
C	Aggregate substitution rate (%)	10	30	50

The BBD scheme was designed with a total of 17 different mix proportion combinations, with three specimens tested for each group, and the average value was taken as the result. Please refer to Table 5 for the concrete compressive strength tests conducted based on the design table. The compressive strength performance of the concrete was tested at 3 days, 28 days, and 90 days, and the obtained data are shown in the Figure 4. The relationship between the compressive strength of the composite recycled aggregate concrete and the influencing factors was established based on characteristic parameters.

Table 5. Fit ratio of BBD scheme design and compressive strength test results (kg/m³).

Number	Cement	Designed Water	NCA	NFA	RFA	Additional Water	WCP	Water Reducer
1	406	142.1	1290	486.5	208.5	13.81	34.75	4.87
2	406	142.1	1290	486.5	208.5	13.81	104.25	4.87
3	406	182.7	1290	486.5	208.5	13.81	34.75	4.87
4	406	182.7	1290	486.5	208.5	13.81	104.25	4.87
5	406	162.4	1290	625.5	69.5	4.60	34.75	4.87
6	406	162.4	1290	625.5	69.5	4.60	104.25	4.87
7	406	162.4	1290	347.5	347.5	23.01	34.75	4.87
8	406	162.4	1290	347.5	347.5	23.01	104.25	4.87
9	406	142.1	1290	625.5	69.5	4.60	69.5	4.87
10	406	182.7	1290	625.5	69.5	4.60	69.5	4.87
11	406	142.1	1290	347.5	347.5	23.01	69.5	4.87
12	406	182.7	1290	347.5	347.5	23.01	69.5	4.87
13	406	162.4	1290	486.5	208.5	13.81	69.5	4.87
14	406	162.4	1290	486.5	208.5	13.81	69.5	4.87
15	406	162.4	1290	486.5	208.5	13.81	69.5	4.87
16	406	162.4	1290	486.5	208.5	13.81	69.5	4.87
17	406	162.4	1290	486.5	208.5	13.81	69.5	4.87

**Figure 4.** The results of compressive strength tests.

2.3.3. Compressive Strength Test

The cube compressive strength tests were conducted in accordance with the “Standard Test Methods for Mechanical Properties of Ordinary Concrete” (GB/T 50081-2016) [33]. The specimen dimensions were 150 mm × 150 mm × 150 mm. After demolding, the specimens were placed in a standard curing room at a temperature of 20 ± 2 °C and a relative humidity of at least 95%. The compressive strength was tested after curing for the specified length of time. The loading rate for the compressive strength test was set at 5 kN/s. The average value of the compressive strength was calculated from three specimens for each mix proportion. The compressive strength test pictures are shown in the Figure 5.



Figure 5. Pictures of compressive strength tests.

2.3.4. SEM Test

The experiment was conducted using a Quanta250 scanning electron microscope, manufactured by FEI Company in the United States. This equipment allows for the observation of the morphological structure of high-molecular-polymer materials. The technical parameters of the Quanta250 scanning electron microscope are as follows:

1. Magnification: $20\text{--}3 \times 10^5$;
2. Acceleration voltage: 0.2–30 kV;
3. Beam current: maximum 2 μA and continuously adjustable;
4. Moving range of the sample table: $X = Y = 50$ mm.

Prior to analysis, the specimens were crushed after curing for the specified length of time, and flat fragments of approximately 1 cm without sharp edges were selected as the test objects. The fragments were soaked in anhydrous ethanol to halt cement hydration. When ready for measurement, the samples were taken out and vacuum dried at 50 °C for 48 h. Before imaging, a conductive layer of approximately 15 nm was formed on the samples by sputtering with gold (Au) to enhance conductivity and prevent electron accumulation from affecting the imaging quality. The accelerating voltage of the instrument was set to 15 kV, with a working distance of approximately 10 mm. The SEM test pictures are shown in the Figure 6.



Figure 6. SEM test picture.

3. Response Surface Result Analysis

3.1. Model Establishment

For response surface analysis, if Quadratic Programming fitting is adopted,

$$q(X_1, X_2, X_3) = c_0 + \sum_{i=1}^3 c_i X_i + \sum_{i=1}^3 \sum_{j=1}^3 c_{ij} X_{ij} + \omega \quad (1)$$

where c_0 , c_i , and c_{ij} are the coefficients to be determined, and the total number of coefficients is 10. That is, $c = c_0, c_1, \dots, c_{10}$. ω is the error. Let $q(X)$ be related to X_1 , X_2 , and X_3 . For a set of determined values of the independent variables X_1 , X_2 , and X_3 , there exists a distribution of $q(X)$. If a mathematical expectation of $q(X)$ exists, $q(X)$ is a function of X_1 , X_2 , and X_3 , and we call it a regression of X_1 , X_2 , and X_3 . Let $(X_{11}, X_{12}, X_{13}, q_1)$, $(X_{21}, X_{22}, X_{23}, q_2)$, and $(X_{31}, X_{32}, X_{33}, q_3)$ be three samples.

The maximum likelihood estimation method is used for parameter estimation: taking $\hat{c}_0$, $\hat{c}_1$, $\hat{c}_2$, and $\hat{c}_3$, such that when $c_0 = \hat{c}_0$, $c_1 = \hat{c}_1$, $c_2 = \hat{c}_2$, and $c_3 = \hat{c}_3$, the existence of takes a minimum, that is, its inverse is 0.

If we take the partial derivative of c_0 , c_1 , c_2 , and c_3 with respect to Y and set it equal to 0, we obtain:

$$X'XC = X'Q \quad (2)$$

$$X = \begin{bmatrix} 1 & X_{11} & X_{12} & X_{13} \\ 1 & X_{21} & X_{22} & X_{23} \\ 1 & X_{31} & X_{32} & X_{33} \end{bmatrix}, C = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix}$$

Multiply both sides of $X'XC = X'Q$ times the inverse of $X'X$, $(X'X)^{-1}$, and we obtain

$$\hat{C} = [\hat{c}_1 \quad \hat{c}_2 \quad \hat{c}_3]^{-1} = (X'X)^{-1}X'Q \quad (3)$$

Equation (3) is the solution equation for BBD.

The compressive strength of concrete is determined by the content of WCP, water–cement ratio, and replacement rate of RFA. Based on Equation (3), a multi-parameter fitting equation was derived from Table 5 to describe the response of different factors on the compressive strength of concrete at 3 days, 28 days, and 90 days. Terms with coefficients smaller than 10^{-9} were omitted from the equation. The resulting compressive strength prediction model is presented in Table 6.

Y_{3d} is the compressive strength at 3 days, representing the short-term strength of concrete; Y_{28d} is the 28-day compressive strength, meaning the middle-term compressive strength. Y_{90} is the 90-day compressive strength and represents the long-term compressive strength.

3.2. Model Verification of Response Surface Analysis

The response surface model essentially represents the implicit functional relationship between the independent variables and the response variable. To address the question of whether there exists a statistically significant relationship between the independent variables and the response variable, it is necessary to conduct significance tests, analysis of variance, and precision tests on the model designed in this study. These tests aim to determine the goodness of fit of the regression results [25].

Table 6. Prediction model of compressive strength.

Time/d	Prediction Model
3	$Y_{3d} = 28.19619 + 0.0714 \times A - 76.24 \times B + 0.295325 \times 30 + 0.26 \times A \times B - 0.002525 \times A \times 30 - 0.355 \times B \times 30 - 0.00027 \times A^2 + 88.3 \times B^2 - 0.001879 \times 30^2$
	$Y_{3d} = 28.19619 + 0.0714 \times A - 76.24 \times 0.4 + 0.295325 \times C + 0.26 \times A \times 0.4 - 0.002525 \times A \times C - 0.355 \times 0.4 \times C - 0.00027 \times A^2 + 88.3 \times 0.4^2 - 0.001879 \times C^2$
	$Y_{3d} = 28.19619 + 0.0714 \times 10 - 76.24 \times B + 0.295325 \times C + 0.26 \times 10 \times B - 0.002525 \times 10 \times C - 0.355 \times B \times C - 0.00027 \times 10^2 + 88.3 \times B^2 - 0.001879 \times C^2$
28	$Y_{28d} = -38.22625 + 0.537 \times A + 356.8 \times B + 0.34725 \times 30 - 2.4 \times A \times B + 0.00425 \times A \times 30 - 0.325 \times B \times 30 + 0.0304 \times A^2 - 396 \times B^2 - 0.004163 \times 30^2$
	$Y_{28d} = -38.22625 + 0.537 \times A + 356.8 \times 0.4 + 0.34725 \times C - 2.4 \times A \times 0.4 + 0.00425 \times A \times C - 0.325 \times 0.4 \times C + 0.0304 \times A^2 - 396 \times 0.4^2 - 0.004163 \times C^2$
	$Y_{28d} = -38.22625 + 0.537 \times 10 + 356.8 \times B + 0.34725 \times C - 2.4 \times 10 \times B + 0.00425 \times 10 \times C - 0.325 \times B \times C + 0.0304 \times 10^2 - 396 \times B^2 - 0.004163 \times C^2$
90	$Y_{90d} = -100.97306 + 1.00685 \times A + 663.865 \times B + 0.643613 \times 30 - 0.73 \times A \times B + 0.00435 \times A \times 30 - 0.66 \times B \times 30 - 0.02223 \times A^2 - 790.3 \times B^2 - 0.006933 \times 30^2$
	$Y_{90d} = -100.97306 + 1.00685 \times A + 663.865 \times 0.4 + 0.643613 \times C - 0.73 \times A \times 0.4 + 0.00435 \times A \times C - 0.66 \times 0.4 \times C - 0.02223 \times A^2 - 790.3 \times 0.4^2 - 0.006933 \times C^2$
	$Y_{90d} = -100.97306 + 1.00685 \times 10 + 663.865 \times B + 0.643613 \times C - 0.73 \times 10 \times B + 0.00435 \times 10 \times C - 0.66 \times B \times C - 0.02223 \times 10^2 - 790.3 \times B^2 - 0.006933 \times C^2$

The coefficient of determination R^2 (R-Squared) is used to evaluate the model's goodness of fit and describe the degree to which the input variables explain the output variables. The closer R^2 is to 1, the better the model is. The calculation method is as follows:

$$R^2 = 1 - \frac{\sum_{s=1}^S (x_s^{mn} - x_s^c)^2}{\sum_{s=1}^S (x_s^c - \bar{x}_s)^2} \quad (4)$$

where S is the number of verification points in the design space; x_s^c is the target value calculated on the response surface of the s group parameters; x_s^{mn} is the target value calculated by the finite element model with the s parameter; and $\bar{x}_s$ is the average of the results calculated by the finite element model analysis. The R^2 determination coefficient represents the degree of difference between the response surface and the actual value. It takes values between 0 and 1, where a value of 1 indicates that they are entirely consistent.

The corrected coefficient of determination (R_{adj}) increased the model's simplicity. It ensured the reliability of the model by eliminating the number of terms that did not improve the accuracy of the model. It is usually analyzed together with the prediction determination coefficient (R_{pred}), which reflects the prediction ability of the model and requires that the difference between the two does not exceed 0.2, as shown in Equation (5):

$$R_{adj} - R_{pred} < 0.2 \quad (5)$$

where R_{adj} is between 0 and 1—the more prominent, the better. The value close to 1 may lead to overfitting situations.

p -values were used for hypothesis testing. If the p -value is less than 0.05, the factor is significant in the model; otherwise, it is insignificant. The p -value of less than 0.01 indicates that the element is highly effective in the model. The F-test method was used to test the hypothesis, as shown in Equation (6):

$$F = \frac{SSR/p}{SSE/(m - p - 1)} \quad (6)$$

where SSR is the sum of regression squares of R ; p is the number of non-constant terms of the response surface function; and p and $m - p - 1$ are the degrees of freedom for SSR and SSE , respectively. For a given confidence level α , the response surface model is considered significant when $F > F_{\alpha}(p, m - p - 1)$.

The results calculated according to the above method are listed in Table 7.

Table 7. Model validation analysis table.

Source	C.V.%	F-Value	<i>p</i> -Value	Significance	R^2	Adjusted R^2	Predicted R^2	Adeq Precision
3 d	1.89	12.47	0.0016	significant	0.9413	0.8658	0.8565	13.8164
28 d	0.792	39.47	<0.0001	significant	0.9807	0.9558	0.9057	19.5297
90 d	0.8093	68.75	<0.0001	significant	0.9888	0.9744	0.9380	19.8009

The predicted R^2 values for the compressive strength at 3 days, 28 days, and 90 days were 0.8565, 0.9057, and 0.9380, respectively. These values, along with the adjusted R^2 values of 0.8658, 0.9558, and 0.9744, respectively, have adjustment differences less than 0.2, indicating reasonable consistency. The Adeq Precision signal-to-noise ratios were measured as 13.8164, 19.5297, and 19.8009, respectively, all of which are greater than 4. This demonstrates that the model established in this study can represent the variation pattern of compressive strength for this specific mix proportion of concrete. The F-values for the models were 12.47, 39.47, and 68.75, indicating the significance of the model. The *p*-values for all models were less than 0.01, indicating high reliability and statistical significance. The model's adjusted determination coefficients were 0.8658, 0.9558, and 0.9744, respectively, indicating that the models can explain 86.58%, 95.58%, and 97.44% of the variation in the compressive strength response. The model's predicted determination coefficients were 0.8565, 0.9057, and 0.9380, respectively, with coefficients of variation (C.V) less than 10%, indicating a good fit between the models and the actual data. Therefore, the aforementioned models can be used for subsequent analysis and optimization.

Figure 7 shows the residual plots for compressive strength at 3 d, 28 d, and 90 d.

From Figure 7, it can be observed that in the compressive strength models at 3 days, 28 days, and 90 days, the normal probability distribution of residuals (a), (c), and (e) aligns along a straight line, while the distribution of residuals with predicted values (b), (d), and (f) appears irregular. Both the measured values and predicted values are located near a straight line. These results indicate that the models have good fitness.

3.3. Analysis of Response Surface Test Results

Table 6 can draw a multifactor response surface plot and two-dimensional contour by verifying the qualified model. The response surface plots show the interaction between the two factors when the remaining factor takes an intermediate value. The interaction of all variables can be clearly shown in the figures. Figures 8–10 show the relationship between the influence of the three factors on compressive strength under the interaction of a single element and two factors.

According to the graph, it can be observed that the compressive strengths at 3 days, 28 days, and 90 days all increase with an increase in the content of WCP. This indicates that the appropriate addition of WCP is beneficial for enhancing the strength of recycled aggregate concrete. From a physical perspective, powdered materials can be considered as fillers. Filling the micro-voids achieves the optimal particle gradation effect, which is consistent with the findings in reference [34]. From a chemical analysis point of view, the test results of oxide content in Section 2.2.2 indicate that WCP is rich in SiO_2 and Al_2O_3 , which gives it a potential pozzolanic effect. This reaction with water produces more cementitious material, which is another important reason for the increase in strength. This conclusion aligns with the findings in reference [35].

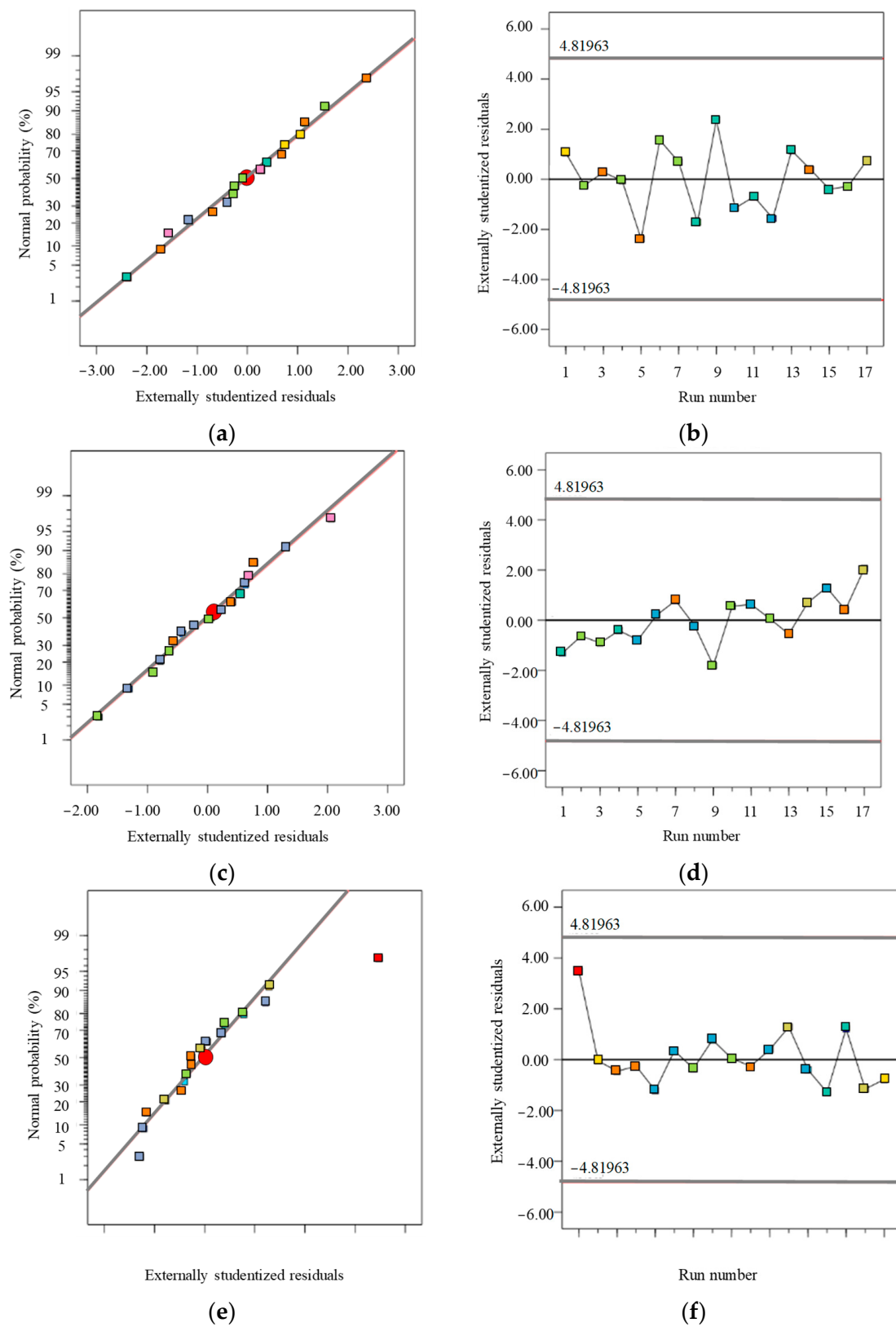


Figure 7. Residual plots for compressive strength. (a) Normal plot of residuals (3 d). (b) Distribution of residuals (3 d). (c) Normal Plot of residuals (28 d). (d) Distribution of residuals (28 d). (e) Normal plot of residuals (90 d). (f) Distribution of residuals (90 d).

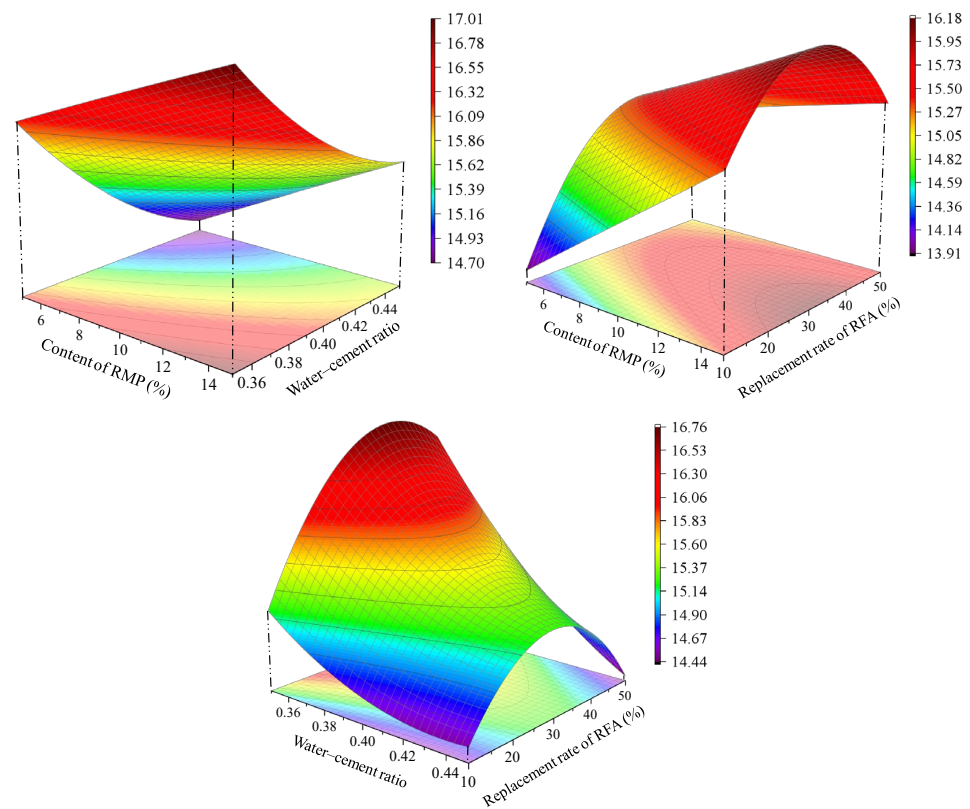


Figure 8. Compressive strength response surface at 3 d.

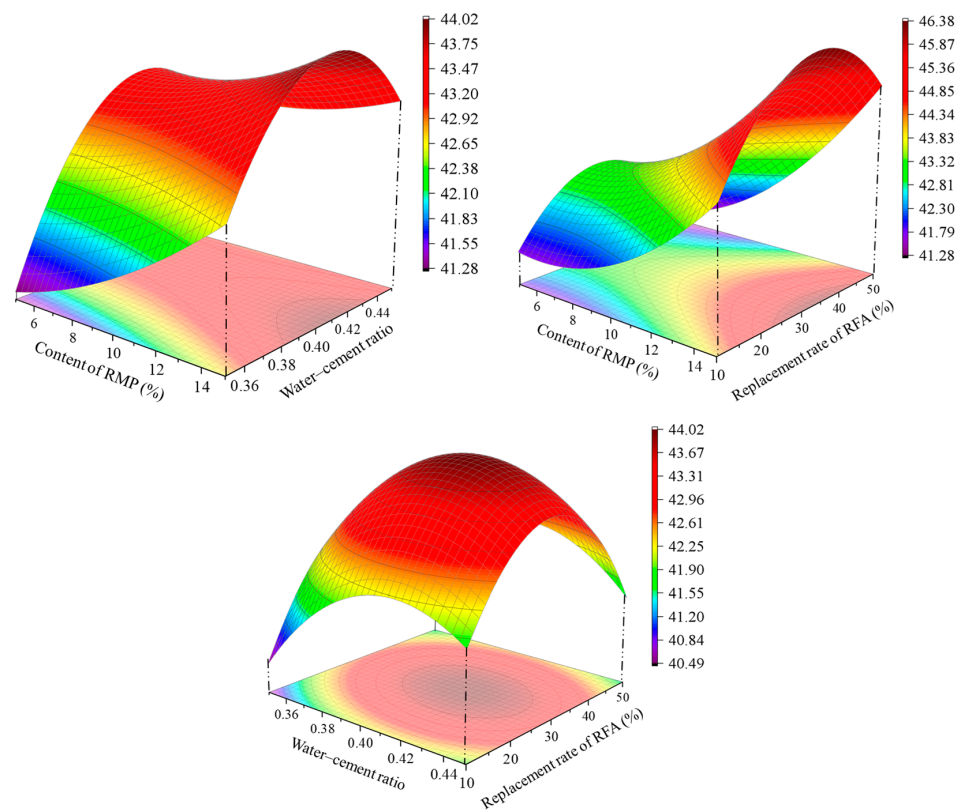


Figure 9. Response surface of compressive strength at 28 d.

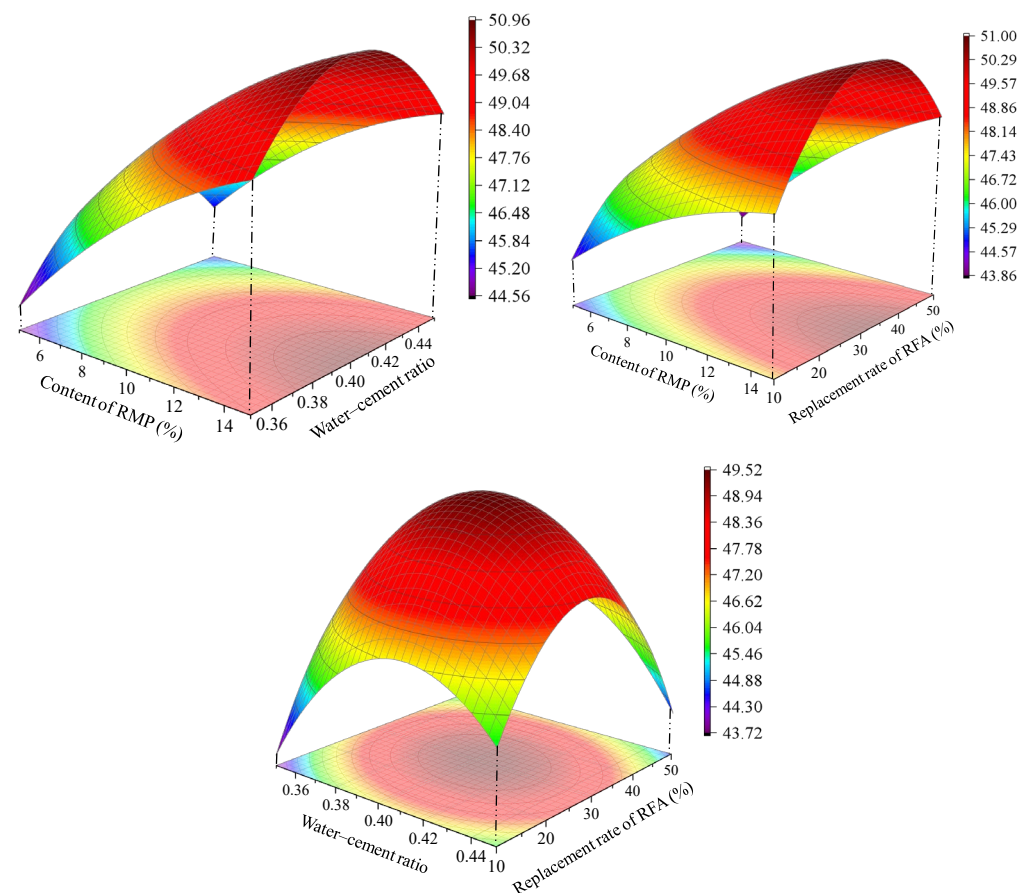


Figure 10. Response surface of 90 d compressive strength.

The compressive strength at 3 days decreases with an increase in the water–cement ratio. The results of compressive strength at 28 days and 90 days indicate that for a water–cement ratio ranging from 0.35 to 0.4, the compressive strength increases with an increase in the water–cement ratio. For a water–cement ratio ranging from 0.4 to 0.45, the compressive strength decreases with an increase in the water–cement ratio. At a water–cement ratio of 0.45, the compressive strength is higher than that at a water–cement ratio of 0.35. This study fully considers the difference in water demand between WCP and RFA compared to natural aggregate. A too low water–cement ratio with insufficient water content may affect the hydration reaction of cementitious materials, resulting in inadequate cementing action and unfavorable compressive strength development. An excessively high water–cement ratio may reduce the compactness of the matrix and increase the capillary porosity due to the presence of free water. This also hinders the increase in compressive strength, which aligns with the findings in reference [36].

The compressive strength at 3 days, 28 days, and 90 days shows an initial increase and then a decrease with an increase in the content of RFA. The maximum compressive strength at 3 days is achieved at a replacement rate of 30%. The test results of aggregate properties in Section 2.1 of this study indicate that the crushing index of RFA is twice that of NFA, resulting in an increase in weak links within the matrix due to its lower strength. This effect is not significant at lower replacement rates of RFA. Instead, it may indirectly adjust the water–cement ratio due to the changes in the water absorption rate of the fine aggregate, which has a positive impact on the compressive strength. However, as the replacement rate increases, the overall continuity of the strength of the matrix becomes discontinuous. The concentration of stress during the compression process leads to a decrease in strength. Similar conclusions can be found in reference [37].

Analysis of variance (ANOVA) was conducted using the model proposed in this study. The significance of factors was determined using the F-test, where F is the ratio of the regression mean square to the residual mean square. The critical value of the factor was set as F_0 , and the probability of F being smaller than F_0 was denoted as p . In this study, the significance of the three factors and their interactions was evaluated based on p -values. A significance level of $p < 0.01$ was considered highly significant, $0.01 < p < 0.05$ was considered significant, and $p > 0.05$ was considered non-significant. The calculated results of compressive strength can be found in Tables 8–10.

Table 8. Analysis of variance of regression models for 3 d compressive strength.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	p-Value
A	1.78	1	1.78	20.88	0.0026
B	3.73	1	3.73	43.79	0.0003
C	0.75	1	0.75	8.82	0.0208
AB	0.01	1	0.01	0.19	0.6693
AC	0.25	1	0.25	3.00	0.1270
BC	0.50	1	0.50	5.92	0.0452

Table 9. Analysis of variance of regression models for compressive strength at 28 d.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	p-Value
A	19.53	1	19.53	167.65	<0.0001
B	0.78	1	0.78	6.71	0.0360
C	0.32	1	0.32	2.75	0.1414
AB	1.44	1	1.44	12.36	0.0098
AC	0.72	1	0.72	6.20	0.0416
BC	0.42	1	0.42	3.63	0.0986

Table 10. Analysis of variance of regression models for compressive strength at 90 d.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	p-Value
A	32.12	1	32.12	221.91	<0.0001
B–B	0.40	1	0.40	2.83	0.1364
C–C	0.16	1	0.16	1.12	0.3246
AB	0.13	1	0.13	0.92	0.3693
AC	0.75	1	0.75	5.23	0.0561
BC	1.74	1	1.74	12.04	0.0104

The results of the analysis of variance for the compressive strength at 3 days indicate that the p -value for factor A is 0.0026, and the p -value for factor B is 0.0003, both of which are less than 0.01. This demonstrates that the influence of the content of WCP and the water–cement ratio on the short-term compressive strength of recycled concrete is highly significant. The p -value for factor C is 0.0208, which is less than 0.05, indicating a significant effect of the replacement rate of RFA on the short-term compressive strength of recycled concrete. The interaction BC has a p -value of 0.0452, also less than 0.05, suggesting that the interaction between the water–cement ratio and the replacement rate of fine aggregate significantly affects the short-term compressive strength of recycled concrete.

The results of the analysis of variance for the compressive strength at 28 days indicate that the p -value for factor A is less than 0.0001, and the p -value for factor B is 0.0360, which is less than 0.01. This demonstrates that the influence of the content of WCP and the water–cement ratio on the middle-term compressive strength of recycled concrete is highly significant. The p -value for factor C is 0.1414, which is greater than 0.05, indicating that the effect of the replacement rate of RFA on the standard compressive strength of recycled concrete is not significant.

The Interaction AB has a p -value of 0.0098, less than 0.01, indicating a significant effect of the interaction between the content of WCP and the water–cement ratio on the middle-term compressive strength. The interaction AC has a p -value of 0.0416, less than 0.05, demonstrating a significant influence of the interaction between the content of WCP and the replacement rate of fine aggregate on the middle-term compressive strength of recycled concrete. On the other hand, the interaction BC has a p -value of 0.0986, greater than 0.05, suggesting that the interaction between the water–cement ratio and the replacement rate of RFA does not have a significant impact on the compressive strength at 28 days.

The results of the analysis of variance for the compressive strength at 90 days indicate that the p -value for factor A is less than 0.0001, demonstrating a highly significant effect of the content of WCP on the long-term compressive strength of recycled concrete. The p -value for factor BC is 0.0104, which is less than 0.05, indicating a significant influence of the water–cement ratio and the replacement rate of RFA on the long-term compressive strength of recycled concrete.

3.4. Mix Ratio Optimization

The response surface is used to analyze the objective equation's solution. The optimal mix ratio of recycled aggregate concrete based on mechanical properties is shown in Table 11.

Table 11. BBD optimized mix ratio.

Test Number	Cement (kg/m ³)	Designed Water	NCA	NFA	RFA	Additional Water	WCP	Water Reducer
1	406	172.96	1290	465.65	229.35	15.19	104.25	4.87

The conclusion reveals that the optimal mechanical performance of concrete is achieved by incorporating 15% of WCP, maintaining a water–cement ratio of 0.43, and substituting 33% of NFA with RFA.

4. Microstructure Analysis Based on Fractal Theory

4.1. Surface Microscopic Morphology Changes

Figure 11 shows typical images of SEM microscopic morphology of ordinary concrete, singly blended RFA, and compound-blended recycled aggregate concrete with the optimized mix ratio given in this paper. The large shapes distributed in the figure are hydrated calcium silicate gel (C–S–H), which is the hydration product of the cementation material and the primary source of compressive strength. The short, rod-like material is ettringite (AFt), which is needle-like in early stages and is filled in during hydration to compact the structure. The volume of ettringite expands during the formation process, and the re-formation of ettringite after the completion of matrix curing may lead to matrix cracking. The small hexagonal pieces are calcium hydroxide (CH), which is brittle and unfavorable for strength.

Comparing Figure 11a,b, after incorporating RFA, the matrix structure was loose and porous at 28 d, and the continuity of hydrated calcium silicate gel was poor. There are multiple penetrating cracks between the hydration products. The RFA comes from the waste concrete, which contains C₂S with inadequate hydration. Compared with ordinary concrete, the slow hydration of dicalcium silicate continues to hydrate slowly in the later hydration period, and the resulting hydrated calcium silicate gel has a significantly smaller size and irregular shape. It cannot be connected as a whole. Comparing Figure 11a–c, the recycled aggregate concrete matrix after compounding is more uniform, flat, and compact. The pores and cracks of (a) (b) between the matrix of the specimen and the voids between the hydration products are filled to form a complete structure. The filling of voids and cracks is strong evidence of solid growth.

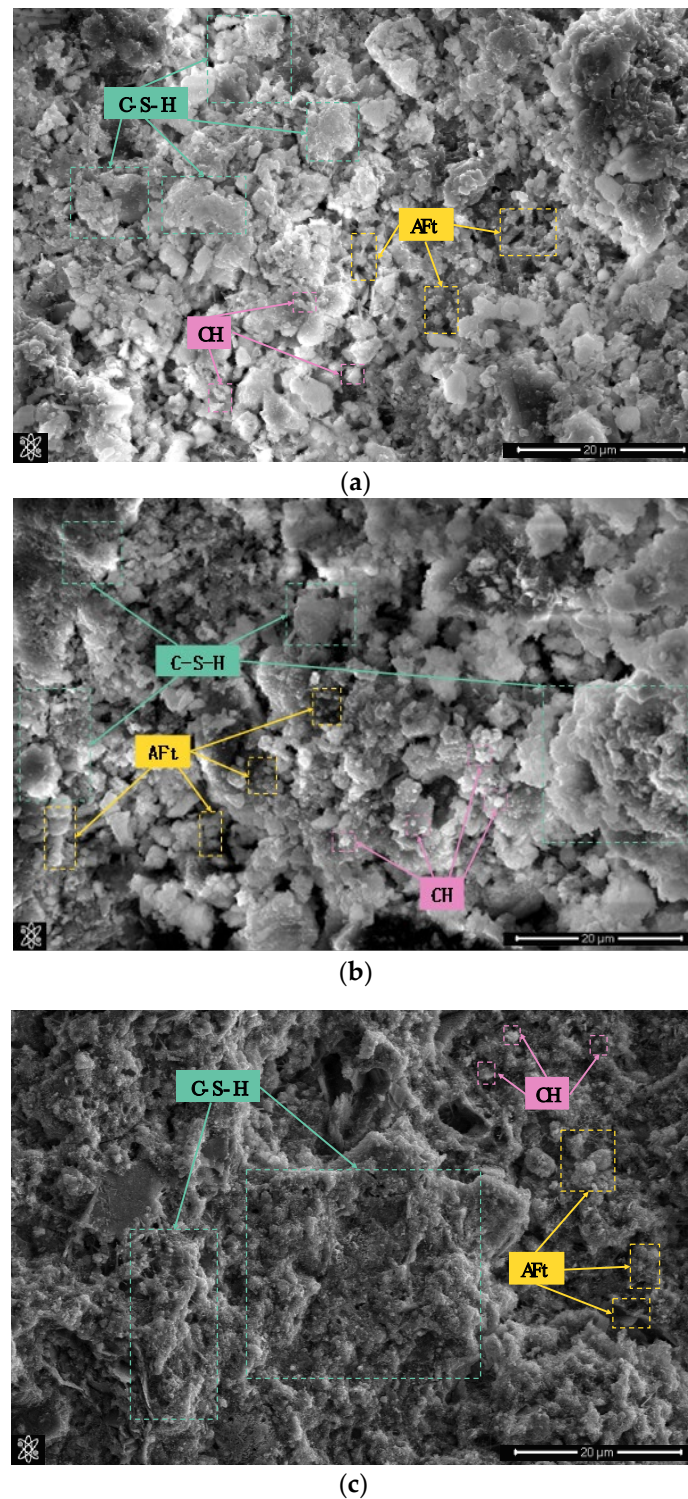


Figure 11. SEM morphology of concrete. (a) Ordinary concrete (unfavourable). (b) 33% RFA. (c) Compounded with 33% RFA and 15% WCP.

4.2. Grayscale Binarization Analysis

SEM images can clearly show the relationship between hydration products and pores. However, direct roughness analysis through SEM images needs to be more accurate. The microscopic picture of SEM needs to be grayscale binarized first [38]. The treatment results are shown in Figures 12–14.

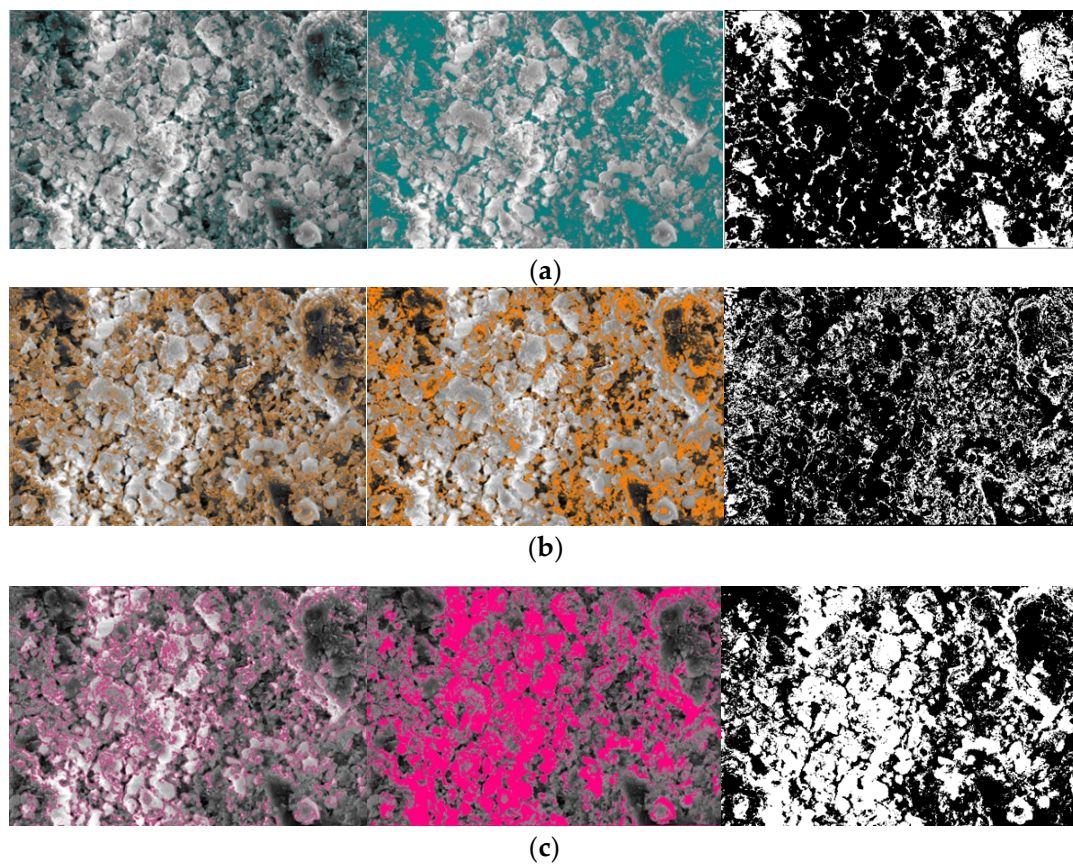


Figure 12. Hierarchical binarization picture of ordinary concrete. (a) F1. (b) F2. (c) F3.

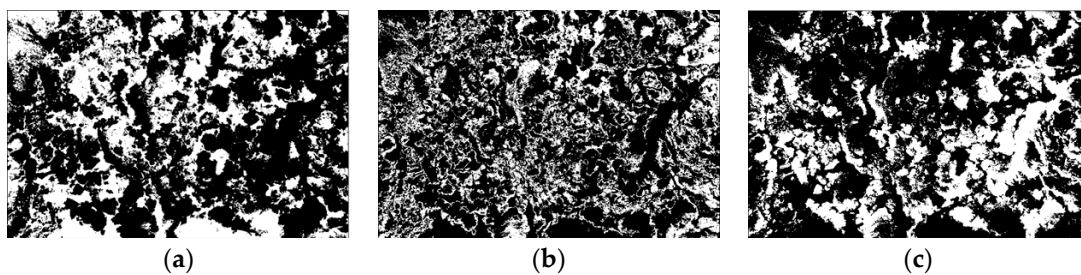


Figure 13. Layered binarization picture of single-doped 33% RFA concrete. (a) F1. (b) F2. (c) F3.

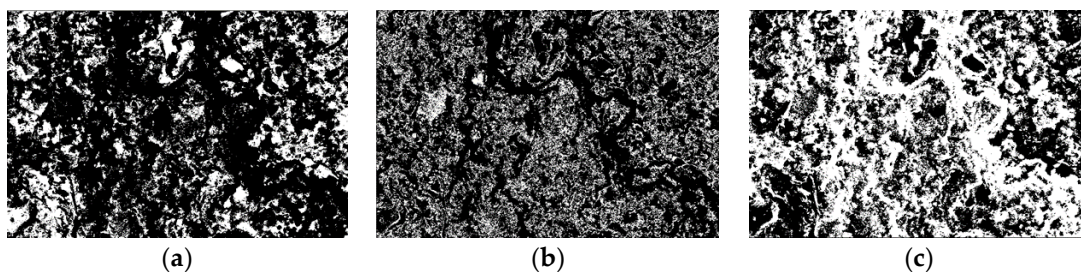


Figure 14. Layered binarization picture of concrete mixed with 33% RFA and 15% WCP. (a) F1. (b) F2. (c) F3.

Take Figure 11a as an example to describe the process of picture binarization. At pixel values from 1 to 255, the contrast of the original image is guaranteed, and the image is denoised. The SEM images were divided into three tomographic objects. F1 (Figure 12a) depicts the hydrated calcium silicate gel layer; F2 (Figure 12b) depicts fillers such as

unhydrated particles, filled powders, Aft, and CH; and F3 (Figure 12c) shows pores and cracks with depths exceeding the limit. Each tomographic object was manually profiled and filled with color, and the supplied picture was binarized. The processed images are only black and white. Black-and-white images indicate the roughness fluctuation of SEM images. In the figure, black represents the research object of the concrete matrix, and white represents pores or cracks. Binary grayscale pictures of concrete mixed with 33% RFA and concrete mixed with 33% RFA and 15% WCP can be obtained using the same method (Figures 13 and 14).

The statistics of the area of the three layers after binarization are listed in Table 12.

Table 12. Statistical table of area of each layer of binarized picture.

Category Level	F1	NAC F2	F3	F1	RAC F2	F3	F1	RAPC F2	F3
Min	10	10	10	10	1	1	1	1	1
Max	13,456	9506	59,879	28,808	6645	56,632	6700	2355	154,697
Range	13,446	9496	59,869	28,798	6644	56,631	6699	2354	154,696
Mean	214	117	283	502	111	283	143	30	428
Sum	116,662	111,834	135,580	164,679	104,010	131,062	108,894	61,593	196,621

Table 12 shows the following: The minimum monomer areas of ordinary concrete F1, F2, and F3 are all 10. The largest monomer area is the hydration product monomer area, 59,879; the filler F2 monomer area is the smallest, 9506. The most extensive total area is that of the hydration product F3, which is 135,580, the smallest is that of F2, 111,834.

When a single admixture regenerates fine aggregate, the minimum area of the monomer is the largest, 10. The minimum sizes of filler and hydration product are the same, 1. The maximum monomer area was 56,632 (that of the hydration product), and the minimum monomer area was 26,645 (filler). The most extensive total area is of pores, 164,679; and the smallest is of filler, 104,010.

Regarding double blending with RFA and WCP, the minimum monomer area is the same. The largest monomer area was that of the hydration product, 154,697; and the smallest was that of the filler 2355. The maximum total size is 196,621, for hydrate; and the minimum is 61,593, for stuffing.

The product area of the three mixture ratios was comprehensively compared. The maximum total porosity is single-doped, and the minimum is complex-doped. Compound mixing is beneficial in reducing the total porosity of the recycled aggregate concrete matrix.

4.3. Fractal Dimension Calculation

This paper introduces the concept of box number to establish three levels of roughness fractal models for SEM images. A fixed-scale cubic box is chosen, and its side length is set to be r_i . The fractal objects are covered with different numbers of packages, and the covering process boxes are not allowed to overlap. This reduces the value of r_i as r_i approaches 0. The logarithm ratio of the number of parcels required for full coverage of the study subject to the logarithm of the box diameter was defined as the box dimension. Let F be any nonempty bounded subset of the S_e space, and for any $r_i > 0$, $M_{r_i}(F)$ denotes the minimum number of cube boxes needed to cover F [39]. There exists k such that

$$R_i \rightarrow 0, M_{r_i}(F) \propto r_i^{-k}$$

Then, k is called the box dimension of F . If and only if there exists a positive value j :

$$\lim_{r_i \rightarrow 0} \frac{M_{r_i}(F)}{r_i^{-k}} = j$$

Taking the logarithm of both sides of the equation,

$$\lim_{r_i \rightarrow 0} (\lg M_{ri}(F) + k \lg r_i) = \lg j$$

$$k = \lim_{r_i \rightarrow 0} \frac{\lg j - \lg M_{ri}(F)}{\lg r} = \lim_{r_i \rightarrow 0} \frac{\lg M_{ri}(F)}{\lg r}$$

A logarithmic coordinate system is established with as the horizontal axis and as the vertical axis. The least squares method fit the curve, and the slope D was the fractal dimension. The fractal dimensions of pores, fillers, and hydration gelling substances are shown in Table 13 through the fractal analysis of the grey-scale pictures of the three types of concrete after stratification.

Table 13. Fractal dimensions.

Category Level	F1	NAC F2	F3	F1	RAC F2	F3	F1	RAPC F2	F3
Fractal dimension	1.71	1.73	1.81	1.71	1.75	1.71	1.67	1.76	1.83

Table 13 shows that the fractal results for pore structure F1 show that NAC and RAC are the same, and the addition of fine aggregate does not significantly affect the pore structure of concrete. However, the fractal dimension of RAPC after double blending is 1.67, which is smaller than that of NAC and RAC, and the WCP plays a physical filling role in the pores. The pore size becomes smaller, improves the pore structure, and positively affects compressive strength.

The fractal results of filler F2 show that the lowest roughness belongs to NAC, and the largest is that of RPC. The filling effect is the best after the composite blending of RFA and regenerated micro-powder, and the singular blending of fine aggregate also plays a particular architectural effect.

The fractal results of hydration gelling product F3 showed that RPC had the highest roughness. The composition analysis of regenerated micro-powder showed that the regenerated micro-powder was mainly derived from old cement paste. Rich in SiO_2 and Al_2O_3 , the regenerated micro-powder has a potentially active volcanic effect, and more hydrated calcium silicate gel is produced after secondary hydration. But this effect is similar to that of concrete. The F3 fractal dimension of a singly blended fine aggregate concrete is the smallest, only 1.71. Much smaller than ordinary concrete and WCP concrete. The surface condition of RFA is more complex, with old mortar and loose structures between it and the entirety. Many needles and short-column ettringite fill the hydration products, making the resulting sheet ettringite less continuous. In addition, the incoming mortar with a loose bond affects the hydration of the newly mixed cement. The selection of the interface transition zone is biased to random, so the fractal dimension of the microimage is small. Discontinuous hydration products hurt compressive strength.

5. Conclusions

Results of an experimental study examining the strength of concrete with singular incorporation of recycled fine aggregate and dual incorporation of RFA and WCP are presented. The interactive effects of the amount of WCP, water–cement ratio, and replacement rate of RFA were investigated using the Box–Behnken design method to determine the optimal mix proportion. Microscopic test images were subjected to layered grayscale binarization processing, and fractal analysis of the product morphology was performed at different levels. The following conclusions can be drawn:

- (1) Based on the response surface experimental analysis of compressive strength, it was found that an appropriate amount of WCP is beneficial for improving the short-, middle-, and long-term strength of concrete. The optimal dosage is 15% by mass of the fine aggregate;

- (2) The water–cement ratio has a significant impact on the compressive strength of concrete. According to the experimental process used in this study, the optimal water–cement ratio is 0.43;
- (3) The replacement of 33% of natural aggregate with RFA does not have a significant effect on compressive strength. This can serve as a guideline for the application of RFA as a substitute for natural aggregate;
- (4) Grayscale binarization processing of the concrete matrix revealed that the concrete with singular incorporation of fine aggregate has the largest pore area, while the concrete with dual incorporation of RFA and WCP has the smallest pore area. The fractal dimension of the pores is negatively correlated with compressive strength;
- (5) Fractal analysis of the hydration products at three levels demonstrated a positive correlation between the fractal dimension of the hydrated calcium silicate gel and compressive strength. The layered fractal model shows superiority in evaluating the compressive strength of concrete.

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