**Preparation and Optimization of Low-Strength Recycled Coarse Aggregate Concrete Based on Response Surface Methodology**

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**ABSTRACT**

This study explores the preparation and optimization of low-strength recycled coarse aggregate concrete using Response Surface Methodology (RSM). With the massive global generation of construction waste, it has become a pressing environmental issue for many countries. Numerous nations are actively seeking ways to recycle construction waste to reduce dependency on natural resources and minimize environmental pollution. In this context, this study begins by testing the basic properties of recycled coarse aggregates derived from construction waste. Through single-factor experiments, the key factors influencing concrete performance and their optimal variation ranges were identified. Subsequently, RSM was employed to optimize the mix design of recycled coarse aggregate concrete, considering the coupling effects between materials. Additionally, by modifying the recycled coarse aggregates, the mechanical properties of the concrete were further enhanced, improving its recyclability. This research provides scientific and technical support for the resourceful utilization of construction waste and the establishment of a closed-loop recycling system.

**Keywords**

Recycled concrete, Damage mechanism, Interfacial transition zones, Fly ash, Slag

1 Introduction

The urgent task of managing industrial solid waste and construction waste in China has gained increasing importance, as the annual production of construction waste now exceeds 1.5 billion tons. Among construction and demolition waste, concrete accounts for 54.21%, while it constitutes 18.42% of the total construction waste. To conserve natural resources and enhance the recycling and utilization of solid waste, converting construction waste into recycled aggregates presents a viable approach to mitigating environmental damage.

Tan Guiying [1] conducted an analysis of the mechanical properties of recycled coarse aggregate concrete, utilizing a grey relational model to predict its performance. The study examined the effects of varying recycled coarse aggregate replacement rates (0%, 30%, 50%, 70%, and 100%) on the compressive, tensile, and flexural strengths of concrete. The results indicated that as the replacement rate of recycled coarse aggregates increased, both compressive and flexural strengths exhibited an overall decline, whereas tensile strength initially increased before decreasing. C. Chella Gifta [2] explored surface modification techniques to enhance the inherent properties of recycled coarse aggregates. André [3], meanwhile, investigated the fire resistance of recycled coarse aggregate concrete, demonstrating that a higher proportion of recycled aggregates reduced the mechanical performance of the concrete after exposure to air.

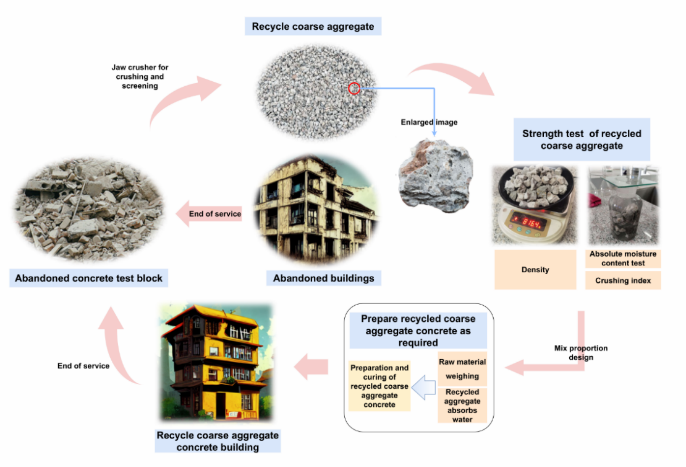
Bian Haobo [4] developed a predictive model for the internal relative humidity and drying shrinkage of recycled aggregate concrete over time. The model highlighted characteristics such as high porosity and complex interfacial transition zones in recycled aggregates, which contribute to a more complicated drying shrinkage mechanism. Qin Wei [5] proposed an innovative method for improving the performance of recycled aggregates by capturing CO2 from industrial emissions through alkali-silica reactions, thereby enhancing their applicability in engineering projects. Zeng Yu [6], using finite element modeling, investigated the use of recycled brick coarse aggregates (RBCA) as a substitute for natural aggregates, developing a customized algorithm to simulate the behavior of RBCA concrete under compression and splitting tensile conditions.

Harish Bongal [7] conducted a comprehensive study on the mechanical and microstructural properties of recycled coarse aggregate concrete, employing a new standard compaction method to analyze the complex dynamics of RCA's influence on concrete performance. Shahzadi Irum [8] explored the performance of fly ash-based geopolymer concrete under heat curing and ambient conditions, finding that the inclusion of recycled aggregates in GPC improved environmental sustainability, with a thorough examination of their impact on GPC behavior. Li Kunpeng [9] investigated the performance of fly ash-basal fiber-reinforced recycled coarse aggregate permeable concrete (RCAPC), using fly ash as a partial cement replacement and basalt fibers to improve the performance of RCA permeable concrete.

Patra Rakesh Kumar [10] studied the properties of concrete incorporating recycled coarse aggregates and rice husk ash, assessing the effects of RCA and RHA on concrete strength and other selected parameters. Tan Guiying [11] further analyzed the mechanical properties and freeze-thaw resistance of recycled brick coarse aggregate concrete, finding that the inclusion of RBA significantly improved frost resistance. Daniel Trento [12] proposed a novel method to mitigate the adverse effects of recycled coarse aggregates in wind turbine blade concrete, addressing the challenges associated with wind turbine blade recycling.

Cai Wu [13] conducted experiments and developed theoretical models for the mechanical properties of steel fiber-reinforced recycled aggregate concrete, investigating the effects of varying amounts of steel fibers and recycled aggregates on the shrinkage performance and compressive constitutive relationships of the concrete. MD Ikramullah [14] examined the durability of concrete pavements containing pre-treated recycled coarse aggregates, focusing on the behavior of RCA and pre-treated recycled coarse aggregates (PCRAs) in alkali-activated concrete (AAC) before and after exposure to marine seawater and acidic environments. Yuan Xiongzhou [15] explored the preparation of high-strength geopolymer concrete using eggshell powder and rice husk ash as raw materials, investigating the effects of eggshell powder as a fly ash substitute in conjunction with RHA on HSGC performance.

Somanshi Agarwal [16] applied data-driven machine learning techniques to predict the compressive strength of self-compacting concrete containing fly ash and recycled coarse aggregates, using a large dataset comprising 444 data points and 10 input parameters for the predictions. M.S. Abo Dhaheer [17] developed a sustainable high-strength concrete by using treated recycled coarse aggregates and recycled fine aggregates, replacing 100% of the fine and/or coarse aggregates with recycled aggregates to create sustainable high-strength concrete (SHSC). M. Tarun Bhargav [18] summarized research advancements on the application of recycled coarse aggregates in prestressed concrete (PSC) components, highlighting the growing adoption of PSC worldwide and evaluating the suitability and durability requirements (such as high compressive strength, high bond strength, and low creep and shrinkage rates) when replacing coarse aggregates with RCA after 7 days.



**Fig 1** Recycled Aggregate Circulation System

Numerous studies conducted by scholars and experts have demonstrated that the recycling of construction waste, coupled with the establishment of a closed-loop recycled aggregate system, as illustrated in Figure 1, can substantially reduce the exploitation of natural resources while yielding significant economic benefits. The primary goal of this study is to identify the optimal range of variables that influence the properties of recycled coarse aggregate concrete through single-factor experiments. Furthermore, response surface methodology is employed to determine the optimal mix proportions. Simultaneously, the performance of the aggregates is enhanced to support the development of a sustainable closed-loop system for recycled aggregates[19-20].

2 Materials and Methods

2.1 Raw Materials

(1) Fly Ash (FA): The fly ash used in this study was produced by the Zhunneng Qiya Power Generation Co., Ltd., Xinjiang, and meets the standards for Grade II fly ash. The fineness of the fly ash is 16%, with a density of 2.45 g/cm³ and a bulk density of 1.36 g/cm³.

(2) Cement: The cement was sourced from Xinjiang Tianshan Cement Co., Ltd., specifically P.0 32.5 cement. The chemical compositions of the cement and fly ash are listed in Table 1.

**Table 1** Chemical Composition Table (%)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Name | Loss on ignition | SiO2 | Al2O3 | Fe2O3 | CaO | MgO | SO3 | k2O | Na2O | R2O | F-CaO |
| Qi Ya FA | 0.82 | 54.49 | 17.14 | 5.68 | 23.09 | 5.16 | 1.81 | 1.32 | 1.92 | 2.79 | 1.01 |
| Cement | 1.0 | 24.11 | 8.35 | 4.05 | 56.01 | - | - | 1.30 | 0.31 | - | - |

(3) Water Reducing Agent (FDN): The water-reducing agent used is C1029 polycarboxylate superplasticizer.

(4) Recycled Coarse Aggregate: The recycled coarse aggregate used in the experiment was sourced from damaged roadbeds as part of the central solid waste project of Xinjiang Zhun dong Energy Investment Group. After being crushed by a jaw crusher and screened, a continuously graded recycled coarse aggregate of 5-32 mm was obtained. The recycled aggregate contains a high amount of old mortar and a complex variety of impurities. The crushing index, water absorption, and apparent density of the recycled aggregate are presented in Table 2.

**Table.2** Performance indicators of recycled coarse aggregate

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Group | Crushing Index (%) | Water Absorption (%) | Moisture Content (%) | Density (kg/m³) |
| 1 | 13.9 | 6.2 | 2.24 | 2.62 |
| 2 | 11.7 | 6.6 | 2.24 | 2.39 |
| 3 | 12.1 | 6.8 | 2.33 | 2.58 |
| Average | 12.6 | 6.5 | 2.27 | 2.53 |

(5) Fine aggregate: natural river sand.

(6) Water glass: Water glass is produced by Xinjiang Xinlian Changsheng Chemical Pharmaceutical Co., Ltd. with a modulus of 1.7 and a concentration of 50.39%.

(7) Water: Water for the Central Solid Waste Project of Xinjiang Zhundong Energy Investment Group Environmental Protection Company.

2.2 Experimental Scheme

2.2.1 Single-Factor Experiment

In the experimental design, natural coarse aggregates were fully replaced by recycled coarse aggregates. The following parameters were set: the water-to-binder ratio (W/B) was set at 0.6, 0.56, 0.52, and 0.48; the fly ash content was set at 0%, 10%, 20%, and 30%; and the dosage of the water-reducing agent was set at 0.16%, 0.18%, 0.20%, 0.22%, 0.24%, and 0.26%. During the experiment, the water content was kept constant, and the sand ratio was fixed at 36.6%. Table 3 presents the mix proportions used in the single-factor experiment.

**Table 3** Mix Proportions for the Single-Factor Experiment

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Group Number | W/B | FA | FDN | Cement | FA | Coarse Aggregate | Fine Aggrega | Pre-added Water | Water | FDN |
| W/B 0.6 | 0.6 | 0 | 0.20 | 303 | 0 | 1149 | 663 | 42 | 181 | 0.606 |
| W/B 0.56 | 0.56 | 0 | 0.20 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.649 |
| W/B 0.52 | 0.52 | 0 | 0.20 | 349 | 0 | 1123 | 649 | 42 | 181 | 0.699 |
| W/B 0.48 | 0.48 | 0 | 0.20 | 379 | 0 | 1107 | 639 | 42 | 181 | 0.757 |
| FA 10 | 0.6 | 10 | 0.20 | 273 | 30 | 1144 | 660 | 42 | 181 | 0.606 |
| FA 20 | 0.6 | 20 | 0.20 | 241 | 60 | 1140 | 659 | 42 | 181 | 0.606 |
| FA 30 | 0.6 | 30 | 0.20 | 211 | 91 | 1136 | 656 | 42 | 181 | 0.606 |
| FDN 0.26 | 0.56 | 0 | 0.26 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.843 |
| FDN 0.24 | 0.56 | 0 | 0.24 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.779 |
| FDN 0.22 | 0.56 | 0 | 0.22 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.713 |
| FDN 0.20 | 0.56 | 0 | 0.20 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.649 |
| FDN 0.18 | 0.56 | 0 | 0.18 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.584 |
| FDN 0.16 | 0.56 | 0 | 0.16 | 324 | 0 | 1136 | 656 | 42 | 181 | 0.519 |

2.2.2 Response Surface Experiment

Based on the results of the single-factor experiment, the optimal range for the water-to-binder ratio (W/B) was determined to be between 0.56 and 0.60, the fly ash content between 10% and 20%, and the water-reducing agent dosage between 0.24% and 0.26%. A response surface experiment was designed to analyze the interaction effects among these three factors and to determine the optimal mix proportion for low-strength recycled coarse aggregate concrete. Table 4 presents the design of the response surface experiment, and Table 5 provides the corresponding mix proportions.

**Table 4** Response Surface Test Plan

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Experiment Order | Group Number | W/B | FA | FDN |
| 1 | 3 | 0.56（-1） | 15%（0） | 0.24%（-1） |
| 2 | 1 | 0.60（1） | 15%（0） | 0.24%（-1） |
| 3 | 10 | 0.56（-1） | 15%（0） | 0.26%（1） |
| 4 | 13 | 0.60（1） | 15%（0） | 0.26%（1） |
| 5 | 12 | 0.56（-1） | 10%（-1） | 0.25%（0） |
| 6 | 6 | 0.60（1） | 10%（-1） | 0.25%（0） |
| 7 | 4 | 0.56（-1） | 20%（1） | 0.25%（0） |
| 8 | 17 | 0.60（1） | 20%（1） | 0.25%（0） |
| 9 | 2 | 0.58（0） | 10%（-1） | 0.24%（-1） |
| 10 | 7 | 0.58（0） | 10%（-1） | 0.26%（1） |
| 11 | 14 | 0.58（0） | 20%（1） | 0.24%（-1） |
| 12 | 11 | 0.58（0） | 20%（1） | 0.26%（1） |
| 13 | 8 | 0.58（0） | 15%（0） | 0.25%（0） |
| 14 | 9 | 0.58（0） | 15%（0） | 0.25%（0） |
| 15 | 16 | 0.58（0） | 15%（0） | 0.25%（0） |
| 16 | 5 | 0.58（0） | 15%（0） | 0.25%（0） |
| 17 | 15 | 0.58（0） | 15%（0） | 0.25%（0） |

**Table 5** Response Surface Test Mix Design

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Experiment Order | Group Number | Cement | FA | Coarse Aggregate | Fine Aggrega | Pre-added Water | Water | FDN |
| 1 | 3 | 294 | 52 | 1077 | 622 | 39 | 194 | 0.90 |
| 2 | 1 | 296 | 52 | 1076 | 621 | 39 | 195 | 0.84 |
| 3 | 10 | 304 | 34 | 1084 | 626 | 39 | 196 | 0.88 |
| 4 | 13 | 289 | 51 | 1081 | 624 | 39 | 197 | 0.85 |
| 5 | 12 | 273 | 68 | 1078 | 622 | 40 | 198 | 0.89 |
| 6 | 6 | 299 | 33 | 1088 | 628 | 40 | 199 | 0.83 |
| 7 | 4 | 283 | 50 | 1085 | 626 | 40 | 200 | 0.87 |
| 8 | 17 | 295 | 52 | 1077 | 622 | 40 | 201 | 0.87 |
| 9 | 2 | 286 | 51 | 1083 | 625 | 40 | 202 | 0.81 |
| 10 | 7 | 290 | 73 | 1066 | 615 | 41 | 203 | 0.91 |
| 11 | 14 | 299 | 53 | 1074 | 620 | 41 | 204 | 0.88 |
| 12 | 11 | 283 | 71 | 1071 | 618 | 41 | 205 | 0.85 |
| 13 | 8 | 275 | 69 | 1077 | 622 | 41 | 206 | 0.86 |
| 14 | 9 | 275 | 69 | 1077 | 622 | 41 | 206 | 0.86 |
| 15 | 16 | 275 | 69 | 1077 | 622 | 41 | 206 | 0.86 |
| 16 | 5 | 275 | 69 | 1077 | 622 | 41 | 206 | 0.86 |
| 17 | 15 | 275 | 69 | 1077 | 622 | 41 | 206 | 0.86 |

2.3 Experimental Method

During the preparation process, due to the high water absorption and porosity of the recycled coarse aggregate, the aggregate was pre-soaked in pre-added water. After mixing for 1 minute, the cement, fine aggregate, water, fly ash, and water-reducing agent were added and stirred continuously for 5 minutes. After thorough mixing, the slump was measured. The mixture was then placed into 150 mm × 150 mm × 150 mm molds, compacted, and sealed for 24 hours. The specimens were cured under standard conditions (20 ± 2°C and relative humidity above 95%) until the designated testing age, after which mechanical performance tests were conducted.

3 Results and Discussion

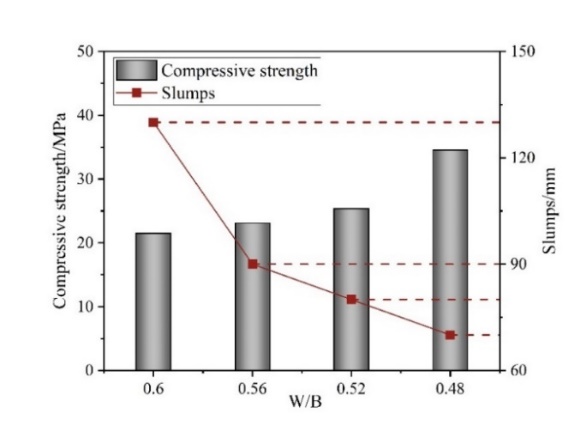
3.1 Single-Factor Experiment Results

After curing the specimens for 28 days under standard conditions, mechanical performance tests were conducted. The results are shown in Table 6.

**Table 6** Mechanical Performance Results

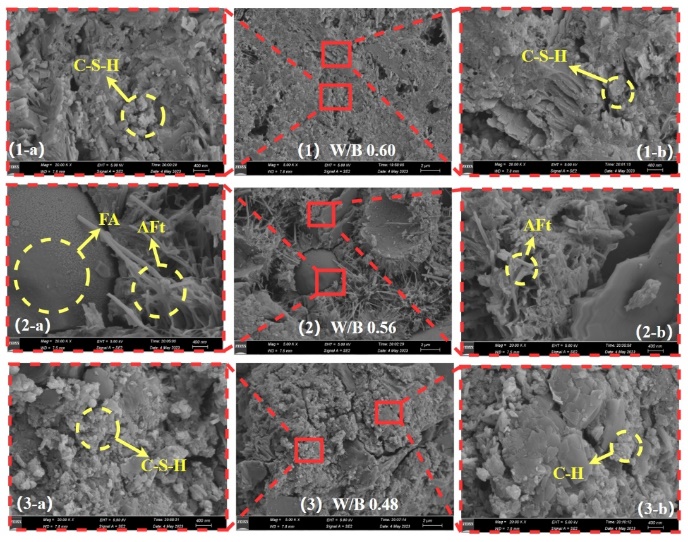
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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Serial Number | Category | W/B | FA (%) | FDN (%) | Sand Ratio (%) | Compressive Strength (MPa) | Serial Number | Category |
| 1 | W/B 0.6 | 0.6 | 0 | 0.20 | 36.60 | 21.52 | 130 | 2.44 |
| 2 | W/B 0.56 | 0.56 | 0 | 0.20 | 36.60 | 23.11 | 90 | 2.28 |
| 3 | W/B 0.52 | 0.52 | 0 | 0.20 | 36.60 | 25.38 | 80 | 2.93 |
| 4 | W/B 0.48 | 0.48 | 0 | 0.20 | 36.60 | 34.57 | 70 | 3.57 |
| 5 | FA 10 | 0.6 | 10 | 0.20 | 36.60 | 20.34 | 75 | 2.30 |
| 6 | FA 20 | 0.6 | 20 | 0.20 | 36.60 | 20.22 | 80 | 1.96 |
| 7 | FA 30 | 0.6 | 30 | 0.20 | 36.60 | 15.66 | 110 | 1.48 |
| 8 | FDN 0.26 | 0.56 | 0 | 0.26 | 36.60 | 24.32 | 90 | 2.50 |
| 9 | FDN 0.24 | 0.56 | 0 | 0.24 | 36.60 | 22.67 | 90 | 2.21 |
| 10 | FDN 0.22 | 0.56 | 0 | 0.22 | 36.60 | 23.62 | 85 | 2.17 |
| 11 | FDN 0.20 | 0.56 | 0 | 0.20 | 36.60 | 22.63 | 85 | 2.18 |
| 12 | FDN 0.18 | 0.56 | 0 | 0.18 | 36.60 | 21.51 | 80 | 2.11 |
| 13 | FDN 0.16 | 0.56 | 0 | 0.16 | 36.60 | 21.96 | 65 | 2.43 |

3.1.1 W/B



**Fig 2** Effect of W/B on mechanical properties

As shown in Figure 2, the compressive strength of recycled coarse aggregate concrete increases significantly as the W/B ratio decreases, while the slump decreases correspondingly. The maximum compressive strength is achieved at a W/B ratio of 0.48. However, since the aim of this experiment is to produce low-strength concrete with high workability, a W/B ratio of 0.6 was selected as optimal for achieving a C20 grade concrete with good workability. Therefore, the optimal W/B ratio was determined to range between 0.56 and 0.60.

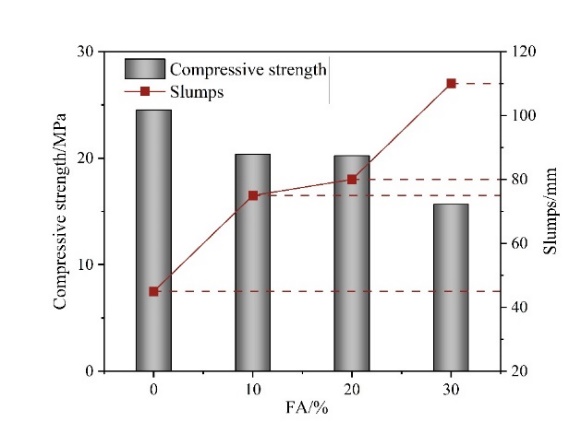


**Fig 3** Microscopic morphology under different W/B ratios

Figure 3 illustrates the microscopic morphology of recycled coarse aggregate concrete under different W/B ratios. The concrete's microstructure becomes denser as the W/B ratio decreases. A comparative analysis of the magnified images shows the significant impact of the W/B ratio on the internal densification of the concrete.

During the hydration process, the formation of calcium silicate hydrate (C-S-H) gel is a primary contributor to concrete strength. At higher W/B ratios, the excess water prevents the hydration products from completely filling the space left by the evaporating water, leading to the formation of pores. At a W/B ratio of 0.48, a substantial increase in the density of flocculent C-S-H can be observed, enhancing the concrete’s mechanical properties.

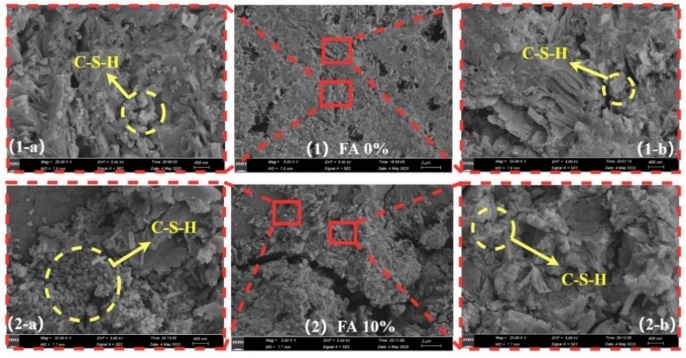
3.1.2 FA



**Fig 4** Effect of fly ash on mechanical properties

Figure 4 shows the influence of fly ash content on the mechanical properties of recycled coarse aggregate concrete. The analysis reveals that as the FA content increases, the compressive strength gradually decreases, while the slump increases significantly. When the FA content reaches 30%, the workability of the concrete reaches its peak; however, its compressive strength falls below 20 MPa.

Considering both compressive strength and workability, the optimal FA content is determined to be within the range of 10% to 20%, allowing the recycled coarse aggregate concrete to meet the C20 strength requirement while achieving satisfactory workability.

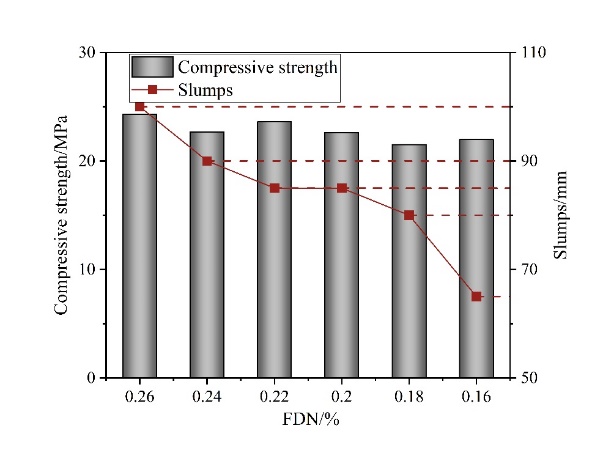


**Fig 5** Microscopic morphology under different FA conditions

Figure 5 displays the microscopic morphology of recycled coarse aggregate concrete at varying FA contents. As FA content increases, the internal structure of the concrete becomes more porous, and the quantity of needle-like ettringite (Aft) products increases. This leads to reduced bonding between the flocculent C-S-H and the aggregates, thereby diminishing the load-bearing efficiency of the C-S-H.

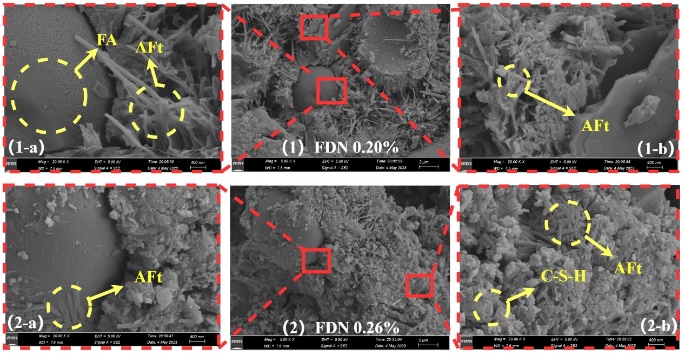
The increased porosity, coupled with the formation of more Aft, results in a reduction in the compressive strength of the recycled coarse aggregate concrete as FA content increases.

3.1.3 FDN



**Fig 6** Effect of FDN on Mechanical Properties

Figure 6 illustrates the effect of FDN content on the mechanical properties of recycled coarse aggregate concrete. The study shows that as the FDN content increases, compressive strength fluctuates around 20 MPa, while the slump increases significantly. When the FDN content reaches 0.26%, the workability of the concrete is optimized, and its compressive strength stabilizes at 20 MPa, fully meeting the C20 strength requirement. Therefore, the optimal FDN content range is determined to be between 0.24% and 0.26%.



**Fig 7** Microscopic morphology under different FDNs

Figure 7 presents the microstructure of recycled coarse aggregate concrete at different FDN contents. With an increase in FDN content, the porosity of the concrete decreases, and the amount of flocculent C-S-H increases, leading to an improvement in the density of the concrete. Additionally, a certain amount of Aft was observed, which contributes to the improvement of early strength in the concrete specimens.

3.2 Response surface test results

The range of variables in the response surface experiment was determined as follows: W/B ratio (A): 0.56, 0.58, and 0.60; FDN content (B): 0.24%, 0.25%, and 0.26%; and FA content (C): 10%, 15%, and 20%. A Box-Behnken response surface design was used, with compressive strength (Y1) and slump (Y2) as the response variables. A regression model was built by performing nonlinear fitting of the experimental data, yielding quadratic polynomial equations for each response variable as shown below:

 (1)

 (2)

Among them, A, B, and C represent the actual values of W/B, FDN, and FA, respectively. Table 7 shows the mechanical performance results of the response test.

**Table 7** Actual Test Results

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Experiment  Order | Group Number | W/B | FA  （%） | FDN  （%） | Compressive strength（MPa） | Split strength（MPa） | Slump  （mm） |
| 3 | 1 | 0.56（-1） | 15（0） | 0.24（-1） | 31.38 | 3.56 | 185 |
| 1 | 2 | 0.60（1） | 15（0） | 0.24（-1） | 30.30 | 2.99 | 175 |
| 10 | 3 | 0.56（-1） | 15（0） | 0.26（1） | 30.14 | 3.48 | 195 |
| 13 | 4 | 0.60（1） | 15（0） | 0.26（1） | 24.07 | 2.49 | 190 |
| 12 | 5 | 0.56（-1） | 10（-1） | 0.25（0） | 23.13 | 2.62 | 210 |
| 6 | 6 | 0.60（1） | 10（-1） | 0.25（0） | 27.83 | 2.70 | 190 |
| 4 | 7 | 0.56（-1） | 20（1） | 0.25（0） | 26.14 | 2.47 | 210 |
| 17 | 8 | 0.60（1） | 20（1） | 0.25（0） | 24.63 | 2.53 | 190 |
| 2 | 9 | 0.58（0） | 10（-1） | 0.24（-1） | 22.68 | 2.21 | 195 |
| 7 | 10 | 0.58（0） | 10（-1） | 0.26（1） | 27.16 | 2.50 | 185 |
| 14 | 11 | 0.58（0） | 20（1） | 0.24（-1） | 24.25 | 2.34 | 195 |
| 11 | 12 | 0.58（0） | 20（1） | 0.26（1） | 22.15 | 2.17 | 200 |
| 8 | 13 | 0.58（0） | 15（0） | 0.25（0） | 20.34 | 2.25 | 220 |
| 9 | 14 | 0.58（0） | 15（0） | 0.25（0） | 25.88 | 2.97 | 180 |
| 16 | 15 | 0.58（0） | 15（0） | 0.25（0） | 23.90 | 2.91 | 190 |
| 5 | 16 | 0.58（0） | 15（0） | 0.25（0） | 32.98 | 4.26 | 180 |
| 15 | 17 | 0.58（0） | 15（0） | 0.25（0） | 24.02 | 3.29 | 190 |

3.2.1 Accuracy analysis of regression model

Table 8 presents the analysis of variance (ANOVA) results for the regression models of compressive strength (Y1) and slump (Y2). The analysis shows that the F-values for the two models are 118.09 and 84.89, respectively, indicating a high level of statistical significance and strong explanatory power of the models. Moreover, the p-values for both models are well below 0.0001, significantly lower than the commonly used significance level of 0.05. Therefore, it can be concluded that both regression models are highly significant statistically and effectively predict the variations in compressive strength and slump.

**Table 8** Regression Model ANOVA Table

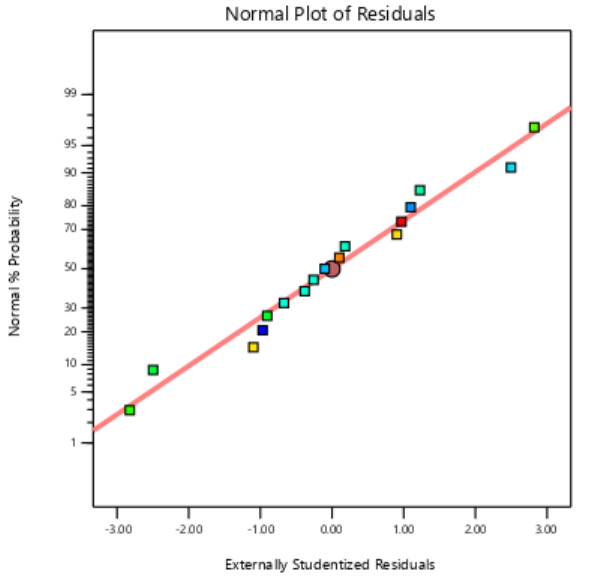
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Source of Response | Compressive Strength（Y1） | | Slump（Y2） | |
| F-value | P-value | F-value | P-value |
| Model | 118.09 | ＜0.0001 | 84.89 | ＜0.0001 |
| A-W/B | 409.88 | ＜0.0001 | 354.37 | ＜0.0001 |
| B-FDN | 63.68 | ＜0.0001 | 109.37 | ＜0.0001 |
| C-FA | 384.81 | ＜0.0001 | 214.37 | ＜0.0001 |
| AB | 7.48 | 0.0292 | 2.19 | 0.1827 |
| AC | 3.69 | 0.0960 | 54.69 | 0.0002 |
| BC | 14.27 | 0.0069 | 2.19 | 0.1827 |
| A² | 15.60 | ＜0.0001 | 1.87 | 0.2143 |
| B² | 16.21 | 0.0050 | 2.79 | 0.1390 |
| C² | 2.04 | 0.1963 | 22.13 | 0.0022 |

From the fitting accuracy results in Table 9, it can be seen that the R2aj and R2pred values of each model are very close to 1, indicating that these models effectively capture and explain the changes in response variables. The small difference between R2pred and R2aj is less than 0.2. The C. of all models V. All of them do not exceed 10%, and the signal-to-noise ratio far exceeds 4, verifying the high fitting accuracy and excellent reliability of the model.

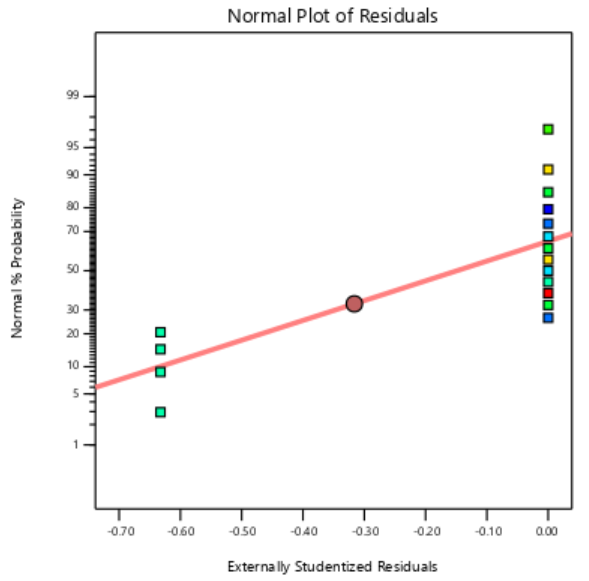
**Table 9** Fitting Accuracy of Regression Models

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Model |  |  |  | （%） | Signal-to-Noise Ratio |
| Compressive Strength | 0.9935 | 0.7188 | 0.9128 | 1.67 | 36.7510 |
| Slump | 0.9909 | 0.9792 | 0.9858 | 0.8761 | 34.7113 |

Referring to the standard residual analysis chart in Figure 8, it is observed that the standardized residual values of all models remain within the range of -3.00 to 3.00. And the distribution of data points is irregular and random, evenly distributed on a straight line. The residuals of the model conform to the characteristics of normal distribution, and no outliers were identified during the fitting process.



(a) Compressive strength

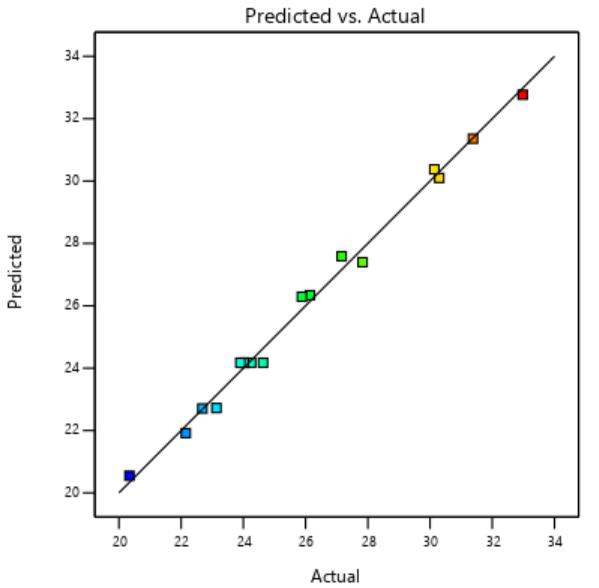


（b）Slump

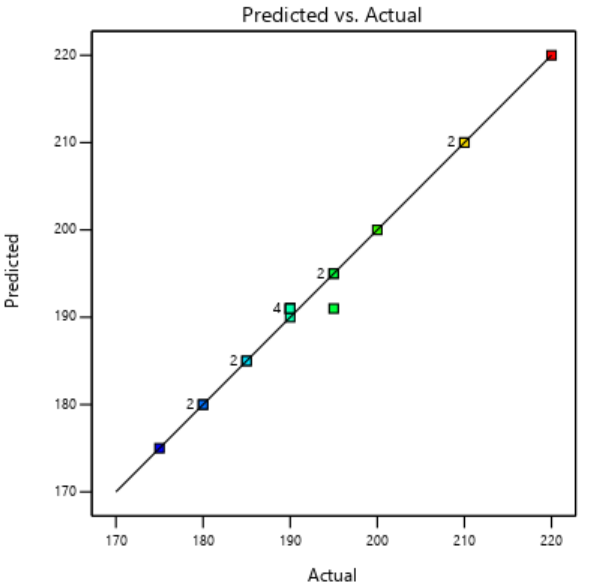
**Fig 8** Residual Analysis of Regression Model

3.2.2 Comparison of Predicted and Experimental Values

To analyze the comparison between predicted values and actual experimental values, a scatter plot was created. As shown in Figure 9, the data points for each response surface model are uniformly distributed along and around the y=x line, indicating that the models exhibit a good fit and excellent agreement with the experimental data. The small errors observed between the predicted and experimental results further confirm the accuracy and reliability of the models.



(a) Compressive strength



(b) Slump

**Fig 9** Comparison between predicted and actual values of the regression model

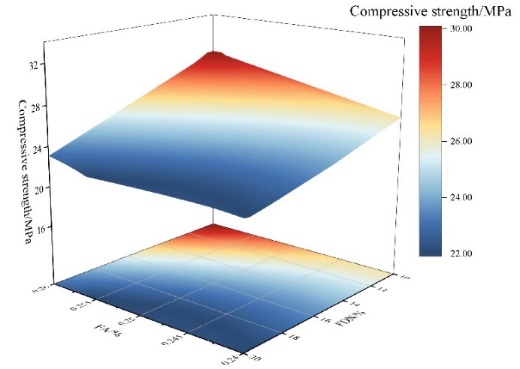
3.2.3 W/B 0.58

The three-dimensional response surface provides an intuitive way to reveal the interaction effects of different factors on the response values. Taking Figure 10 as an example, the interaction between FDN and FA on compressive strength and slump was studied with a W/B ratio of 0.58.

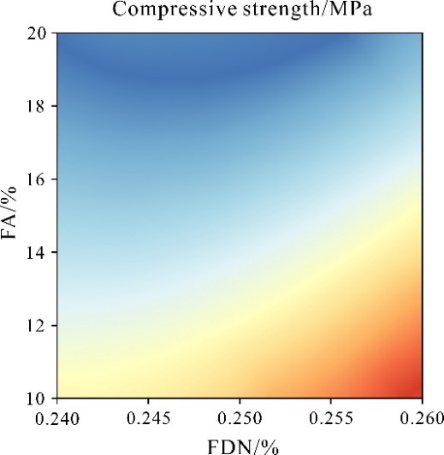
The results indicate that as the FDN content increases, the 28-day compressive strength gradually rises. Specifically, when the FDN content is increased from 0.24% to 0.26%, the strength improves by approximately 6%. The corresponding contour plot shows an arc-shaped curve, suggesting that there is an optimal combination of FDN and FA content for achieving maximum compressive strength.

On the other hand, at higher FA content levels, the compressive strength slightly decreases as FA content increases. This phenomenon is represented by a parabolic shape in the contour plot, indicating that excessive FA content within the current experimental range is detrimental to the development of matrix compressive strength.

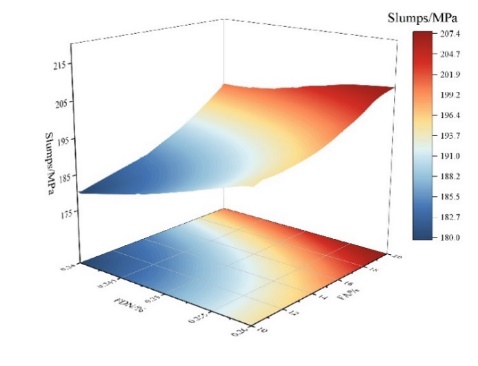
As for the slump, it increases with the rising content of both FDN and FA, and the observed curves demonstrate that FA has a more pronounced impact on slump. Overall, the three-dimensional response surface clearly illustrates the interaction between variables, helping to identify the key factors for optimizing concrete mix proportions.



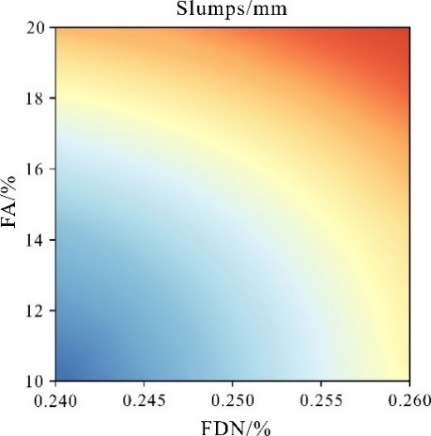
(a) W/B0.58 compressive strength curve



（b）W/B0.58 compressive strength contour map



(c) W/B0.58 Slump Curve



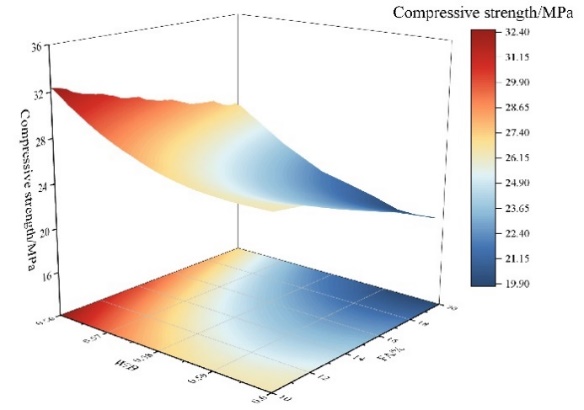
(d) W/B0.58 Slump Contour Map

**Fig 10** Effects of W/B and FDN Coupling on Performance

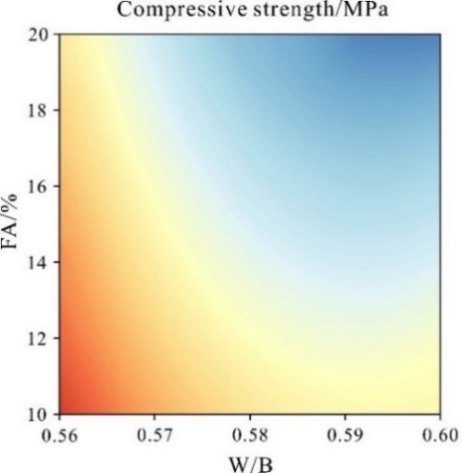
3.2.4 FDN 0.25%

Figure 11 illustrates the response surface and contour plots showing the interaction effects of W/B and FA on concrete compressive strength and slump at an FDN proportion of 0.25%. The results indicate that as the W/B ratio decreases, the 28-day compressive strength gradually increases. However, when the FA content is increased from 10% to 20%, the compressive strength significantly decreases. The corresponding contour plot shows an arc-shaped curve, indicating the presence of an optimal mix ratio.

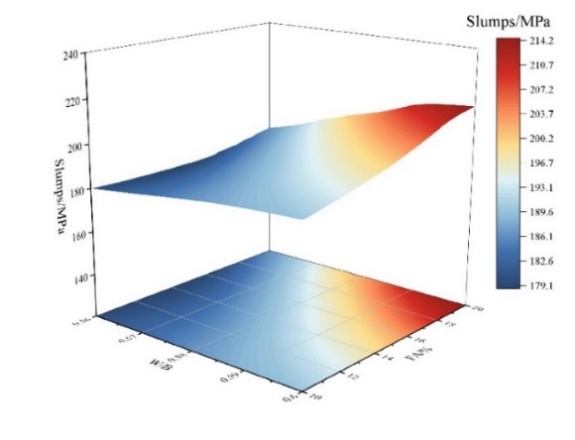
When the FA content reaches 20% and the W/B ratio is 0.60, the slump reaches its maximum value, with the contour plot showing a diagonal straight line trend. Compared to compressive strength, the optimal mix effect on slump is less pronounced, but the response surface method can further refine the determination of the best admixture proportions.



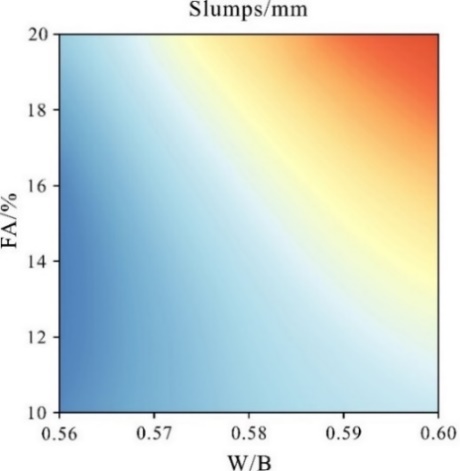
(a) FDN0.25% compressive strength curve



(b) FDN0.25% compressive strength contour map



(c) FDN 0.25% slump curve



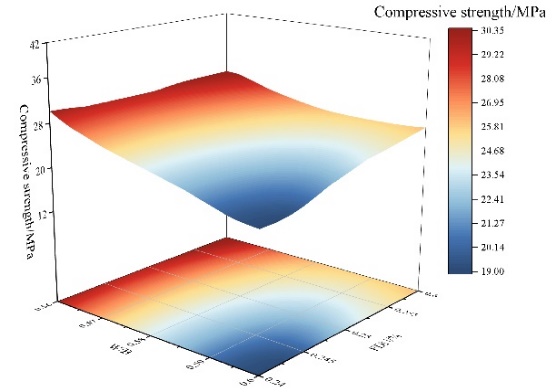
(d) FDN 0.25% slump contour map

**Figu 11** Effects of FA and W/B Coupling on Performance

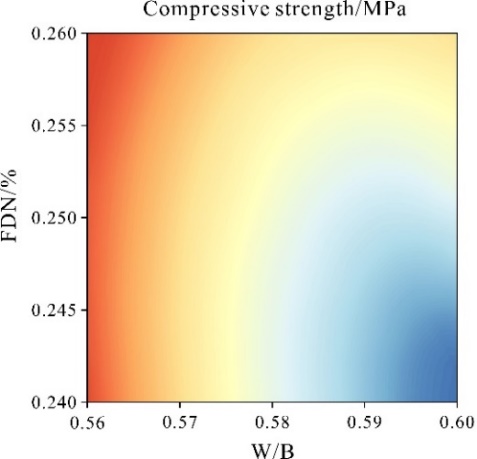
3.2.5 FA15%

Figure 12 shows the response surface and contour plots illustrating the interaction effects of W/B and FDN on concrete compressive strength and slump at an FA content of 15%. As the W/B ratio decreases, the 28-day compressive strength gradually increases. When the FDN content is increased from 0.24% to 0.26%, the compressive strength shows a slight improvement. The corresponding contour plot exhibits a parabolic shape, indicating the presence of an optimal mix ratio.

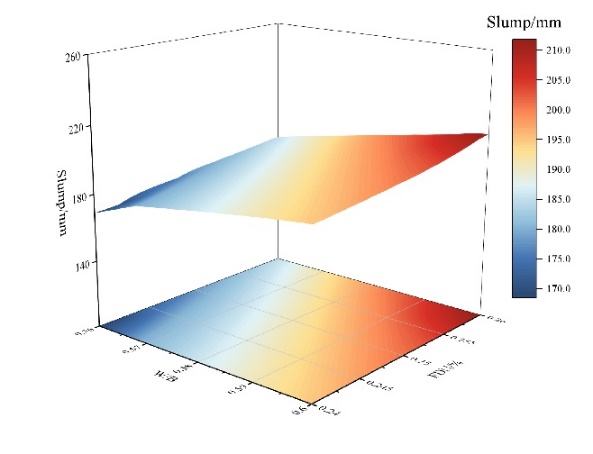
When the FDN content is 0.26% and the W/B ratio is 0.60, the slump reaches its maximum value, with the contour plot showing a diagonal straight line trend. The optimal mix effect on slump is less pronounced compared to compressive strength, but the response surface method can still be used to determine the best admixture proportions.



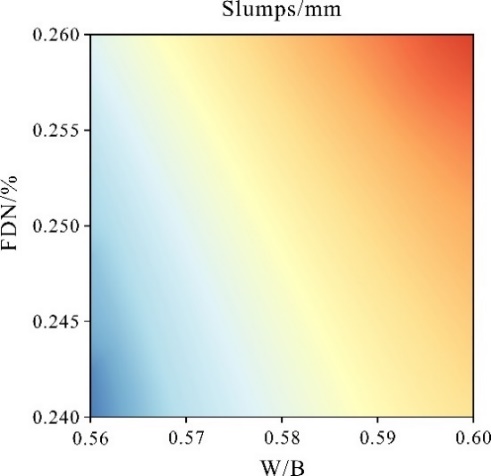
(a) FA15% compressive strength curve



(b) FA15% compressive strength contour map



(c) FA15% slump curve

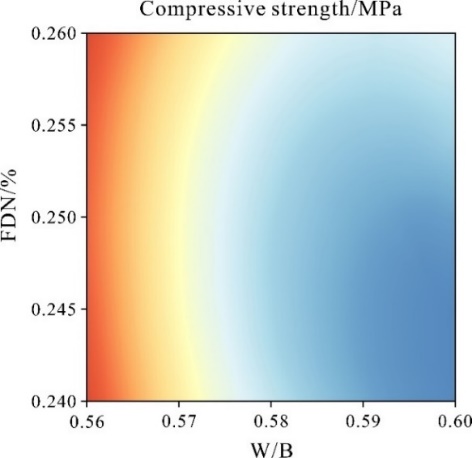


(d) FA15% slump contour map

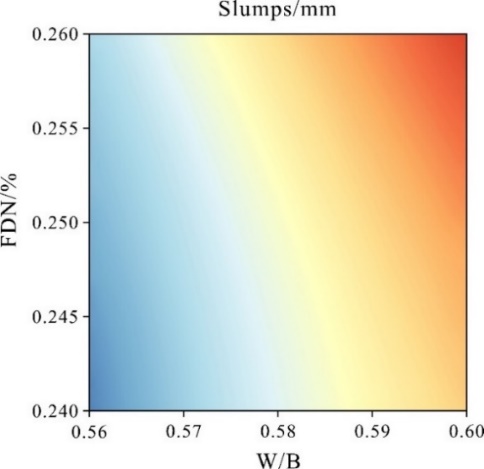
**Fig 12** Effects of FDN and W/B Coupling on Performance

3.3 Optimal Mix Proportion

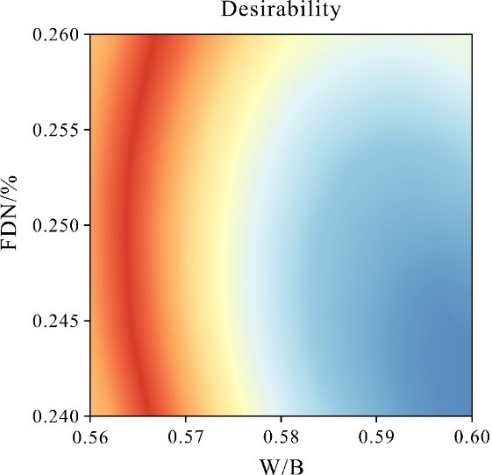
Based on the analysis of the response surface experiment results and the study of the hydration mechanism, the optimal mix proportion for recycled coarse aggregate concrete was calculated as follows: W/B ratio of 0.56, FDN content of 0.25%, and FA content of 19%. The response surface experiment predicts a compressive strength of 27 MPa and a slump value of 190 mm. Figure 13 illustrates the response surface's optimal predicted results.



(a) Prediction of compressive strength



(b) predicti on of slump



(c) Optimal result chart

**Fig 13** Response Surface Prediction Results

3.4 Optimization and Modification of Recycled Coarse Aggregate

3.4.1 Mechanical Properties

The repeated recycling of coarse aggregates tends to reduce material reactivity, necessitating preliminary modification of the recycled coarse aggregate to reactivate its properties. This modification aims to enhance the mechanical properties and density of recycled coarse aggregate concrete. Unlike natural aggregates, recycled coarse aggregates are coated with a layer of old mortar, which has partially lost its reactivity. The primary components of this old mortar include silicon (Si), calcium (Ca), and a certain amount of aluminum (Al).

In this study, a common method of alkali-activated cementitious material was employed to modify the recycled aggregates. The comparative results of the modified properties are presented in Table 8.

**Table 8** Performance indicators of recycled coarse aggregate

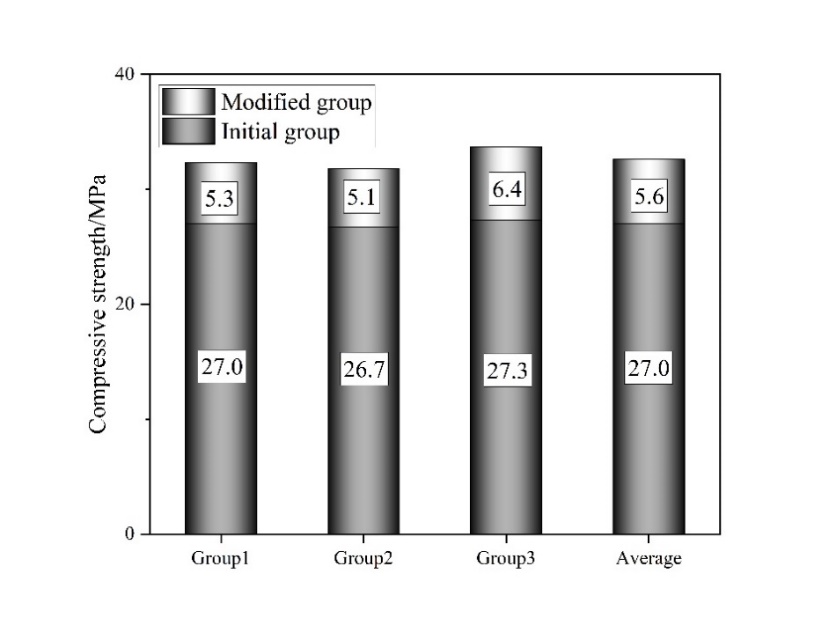
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Number of groups | Crushing index（%） | Water absorption rate（%） | Moisture content（%） | Density /（kg·m-3） |
| Original | 12.6 | 6.5 | 2.27 | 2.53 |
| Modified | 10.8 | 5.5 | 2.40 | 2.55 |

The modified recycled coarse aggregate was blended according to the optimal mix proportions determined by the response surface method. The specific parameters were as follows: W/B ratio of 0.56, FDN content of 0.25%, and FA content of 19%. After preparing the samples and subjecting them to standard curing, mechanical performance tests were conducted. The changes in the mechanical properties of the modified recycled coarse aggregate concrete are presented in Table 9.

Figure 14 illustrates the extent of strength improvement in the modified concrete based on the original materials. The optimization and modification of the recycled coarse aggregate resulted in a 20% increase in compressive strength of the concrete.

**Table 9** Performance indicators of recycled coarse aggregate

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Group | W/B | FDN（%） | FA（%） | Compressive Strength  （MPa） | Slump（mm） |
| Original 1 | 0.56 | 0.25 | 19 | 27.0 | 190 |
| Original 2 | 0.56 | 0.25 | 19 | 26.7 | 195 |
| Original 3 | 0.56 | 0.25 | 19 | 27.3 | 190 |
| Modified 1 | 0.56 | 0.25 | 19 | 32.3 | 190 |
| Modified 2 | 0.56 | 0.25 | 19 | 31.8 | 185 |
| Modified 3 | 0.56 | 0.25 | 19 | 33.7 | 190 |
| Average | 0.56 | 0.25 | 19 | 32.6 | 190 |

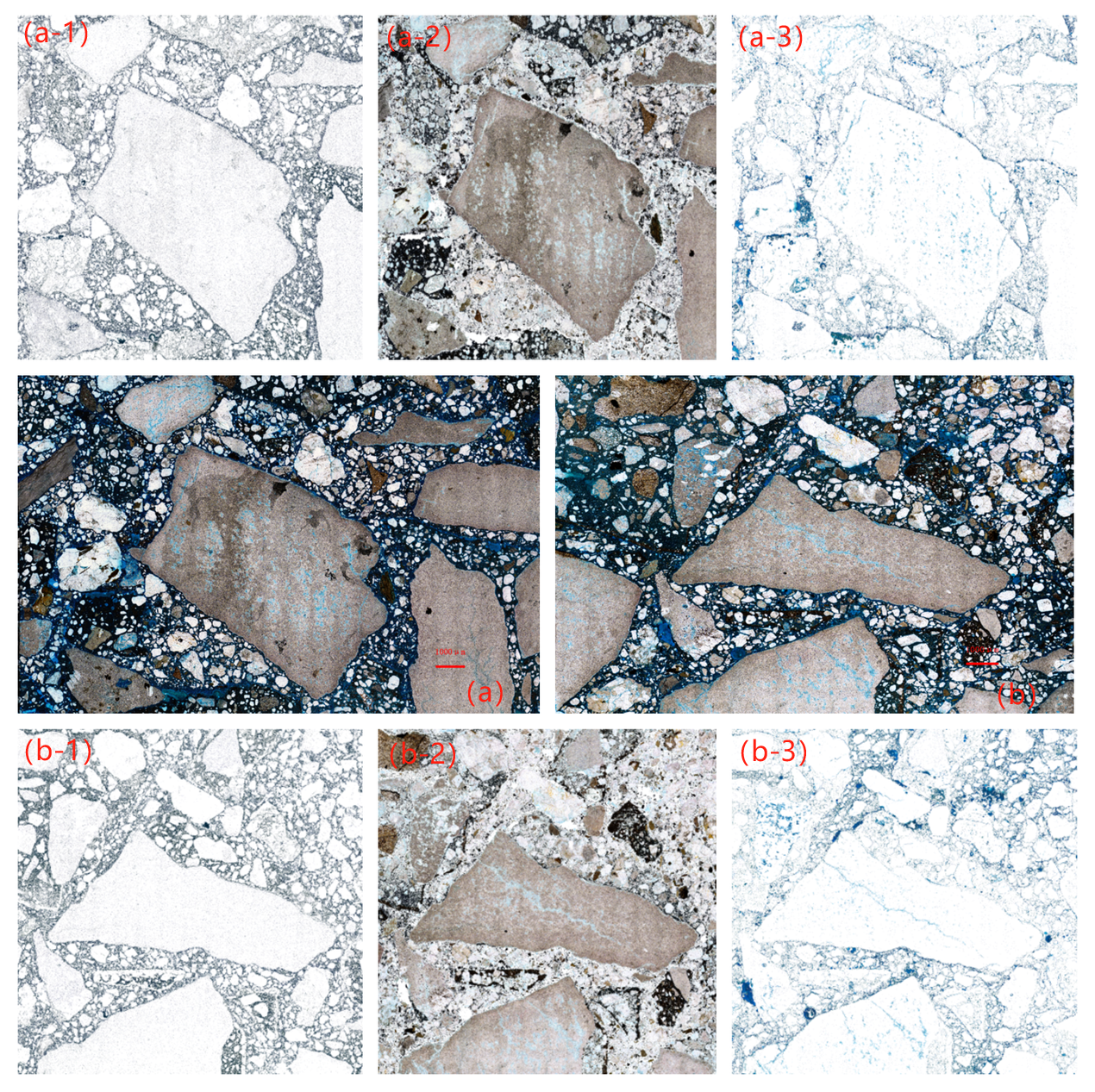


**Fig 14** Comparison of Performance of Recycled Aggregate Modified Concrete

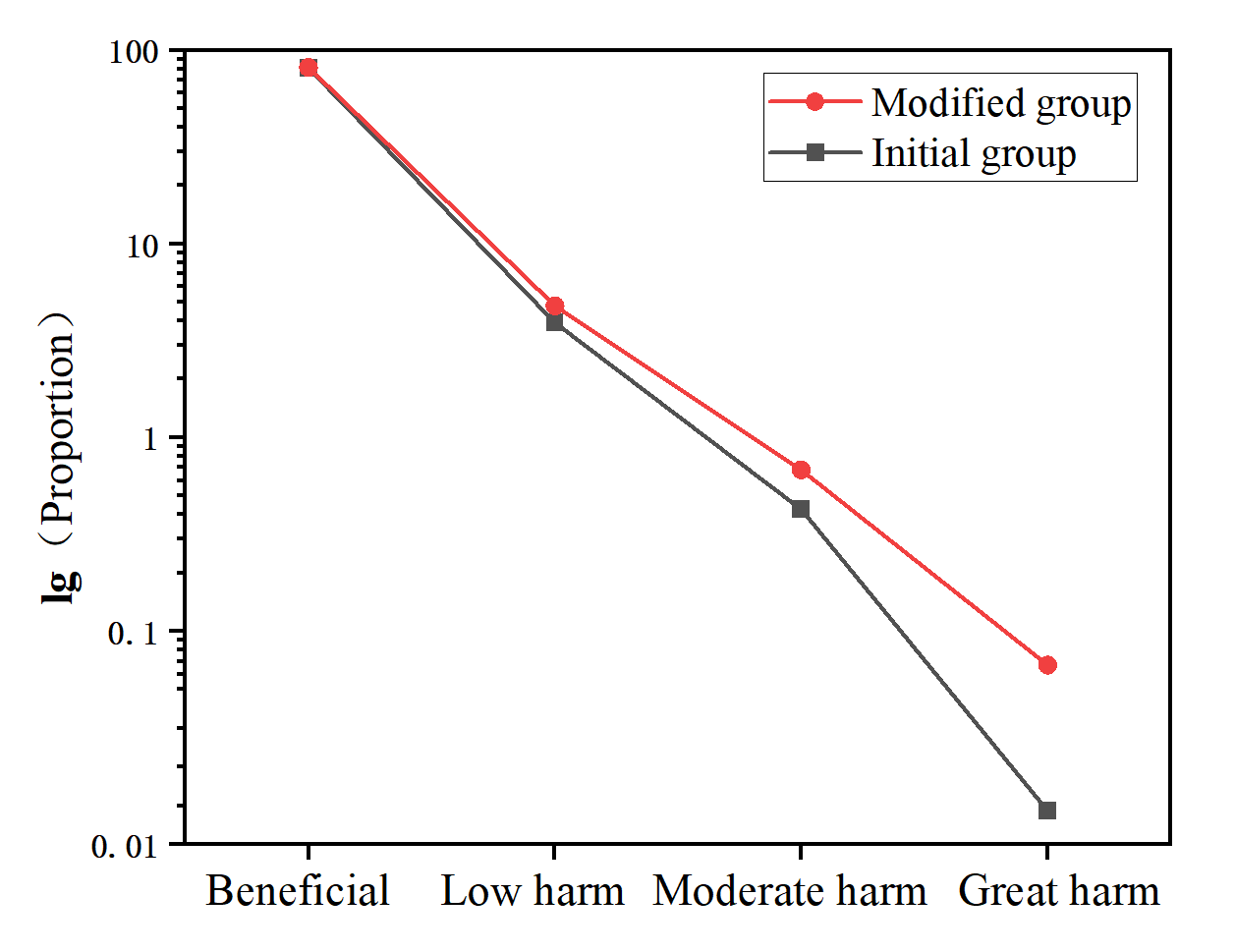
3.4.2 Pore Structure Changes

Figure 15 displays the bubble morphology of the aggregate, where Figure 15(a) represents the original group and Figure 15(b) represents the modified group. By modifying the recycled coarse aggregate using water glass, the water glass initiates preliminary modification of the old mortar in an alkaline environment, leading to the formation of calcium aluminum silicate hydrate (C-A-S-H).

Additionally, the incorporation of fly ash (FA) in the alkaline environment results in the breakdown of its glassy structure, enhancing its hydration process. This modification further reduces the porosity of the recycled coarse aggregate concrete, contributing to improved mechanical properties.



**Fig 15** Aggregate Bubble Morphology Diagram



**Fig 16** Bubble Proportion Chart

This improvement in the concrete’s microstructure results in a denser matrix, with fewer large detrimental voids, while maintaining beneficial voids necessary for workability and freeze-thaw resistance. To further optimize performance, focus should be placed on refining the use of alkali activators, potentially combining them with other surface treatments like silica fume, to maximize strength and durability. Additionally, real-time monitoring of bubble formation during mixing and curing could provide feedback for ongoing adjustments, ensuring the balance between beneficial and harmful voids is maintained. This approach promotes a closed-loop recycling process, enhancing the mechanical properties of recycled concrete while contributing to sustainability in construction.

4 Conclusions

1.Optimal Material Proportions: Through single-factor experiments, the optimal ranges for key components, including fly ash (FA), water-to-binder ratio (W/B), and superplasticizer (FDN), in recycled coarse aggregate concrete were identified, and their influence on performance was clarified.

2.Optimal Mix Design: Using response surface methodology, the interactions among FA, FDN, and W/B were analyzed, leading to the establishment of the optimal mix proportions for recycled coarse aggregate concrete.

3.Hydration Mechanism: The hydration process of low-strength recycled coarse aggregate concrete was examined. Controlling the W/B ratio and FDN content significantly impacted the concrete's density, mechanical properties, and microstructure. An increase in FA content disrupted hydration, forming needle-like ettringite (Aft), which contributed to a reduction in compressive strength.

4.Aggregate Modification: Modifying recycled coarse aggregates with water glass improved their crushing index, water absorption, and density. When these modified aggregates were used in concrete with the optimal mix design, a 20% improvement in compressive strength was achieved, enhancing the viability of a sustainable, closed-loop recycling process for concrete.

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