

# *Mix Design and Preparation Process of Environmentally Friendly Coarse Aggregate Ultra-High Performance Concrete*

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**Abstract:** The application of recycled aggregates still suffers from problems such as large performance fluctuations and insufficient stability in terms of interface defect control, mix proportion matching, and structural density adjustment. Therefore, this paper constructs a synergistic method encompassing aggregate pretreatment, mix proportion design, and preparation process optimization for the environmentally friendly coarse aggregate UHPC system. At the material level, pore defects in recycled coarse aggregates are reduced through crushing, screening, and surface strengthening treatment. In mix design, the multi-admixture composite system is optimized based on particle packing theory, and the slurry and aggregate are precisely matched through volume distribution and interface correction methods. During the preparation process, staged feeding and efficient stirring processes are used to improve the uniformity of coating, and vibration compaction and temperature-controlled curing are combined to strengthen the internal structure densification, thereby achieving synergistic control over the development of fluidity, porosity, and strength. The results show that under the conditions of coarse aggregate volume fraction of 0.30%, water-cement ratio of 0.21, and silica fume content of 15%, the system exhibits the best comprehensive performance, with a spread of up to 720 mm and a T500 of 4.5 s, demonstrating good workability. Simultaneously, the 28-day compressive strength reaches 145.2 MPa, an increase of approximately 12.3% for the higher aggregate content group, while the porosity decreases to 3.9%.

## 1. Introduction

Traditional UHPC generally relies on natural high-quality aggregates and high usage cementitious materials, which not only consume large amounts of resources and have a heavy

environmental burden, but also have high costs in practical engineering applications, limiting its large-scale promotion [1]. At the same time, the application of environmentally friendly coarse aggregates (especially recycled coarse aggregates) in UHPC still faces many bottleneck problems, such as complex pore structure, high water absorption rate, weak interface transition zone, and large performance fluctuations. These factors make it difficult for materials to meet expected requirements in terms of workability, mechanical properties, and long-term stability [2-3].

In response to the above issues, this article takes environmentally friendly coarse aggregate ultra-high performance concrete as the research object, and constructs an overall technical route of material processing mix design preparation process collaborative optimization. At the material level, the performance of coarse aggregates is improved through pre-treatment methods such as crushing, screening, and surface strengthening; In terms of mix design, based on the theory of particle packing and the synergistic mechanism of multiple admixtures, the matching relationship between the cementitious material system and the water cement ratio is optimized; In terms of preparation process, combined with staged feeding and efficient mixing strategy, and combined with vibration compaction and reasonable curing system, the densification control of material structure is achieved.

## 2. Related Works

In recent years, research on predicting concrete performance and optimizing mix proportions has gradually shifted from traditional empirical methods to data-driven and multi-scale coupling methods. Dai et al. used 9 machine learning models to predict the relative dynamic modulus of elasticity and mass loss rate of concrete. The results showed that the nonlinear model was overall superior to the linear method, with GBDT and CatBoost showing the best performance in different indicators, and combined with Monte Carlo method to achieve mix proportion optimization [4]. This study demonstrates that machine learning methods have strong predictive and optimization capabilities in complex multi parameter coupled problems.

In terms of functional concrete and special applications, Barbhuiya et al. systematically analyzed the material composition and shielding mechanism of radiation resistant concrete, pointing out that density, thickness, and aggregate type play a decisive role in radiation attenuation performance, and evaluated its performance by combining gamma spectroscopy and Monte Carlo simulation methods [5]. On this basis, Li et al. proposed an aggregate ratio optimization method based on particle swarm optimization algorithm, and demonstrated its good performance in neutron and gamma ray shielding through Geant4 simulation and experimental verification [6]. The above research indicates that combining optimization algorithms with physical simulations can achieve collaborative improvement in multi-objective performance. However, such research mostly focuses on the design of shielding performance of functional concrete, and the attention to multi-scale structural densification and aggregate interface control in UHPC systems is still relatively limited.

In terms of green material substitution, Jalal et al. compared and analyzed geopolymers concrete with ordinary Portland cement concrete, and found that geopolymer systems significantly reduce carbon emissions while ensuring mechanical properties, demonstrating good sustainability [7]. Boakye et al. explored the feasibility of coconut shell as a substitute material for coarse aggregates, and the results showed that it could maintain basic mechanical properties at a certain substitution rate, but its workability decreased, and the improvement effect of additives on high dosage systems was limited [8]. These studies provide important references for the replacement of natural aggregates, but also reflect the problem of difficulty in balancing workability and strength when using recycled or bio based aggregates in high-performance concrete.

### 3. Methods

#### 3.1 Environmentally friendly Coarse Aggregate Processing and Performance Control Methods

##### 3.1.1 Design of Pre-treatment Process for Recycled Coarse Aggregate

To address the issues of complex sources of recycled coarse aggregates, high impurity content, and obvious interface defects, a multi-stage pretreatment process with "crushing screening impurity removal" as the core is constructed. Firstly, by controlling the particle size distribution of the aggregate through graded crushing, excessive crushing can be avoided, which can lead to excessive particle edges and internal microcrack propagation; Secondly, multi-stage screening is used to achieve precise division of particle size intervals and improve the continuity of gradation; By combining wind selection and water washing processes, lightweight impurities, dust, and residual mortar can be effectively removed, thereby improving the purity and stability of the aggregate.

On this basis, surface strengthening treatment is introduced to improve the weak interface characteristics of recycled aggregates. Remove loose and adhered mortar layers through mechanical abrasion or mild acid washing to reduce the density of interface defects; Further modification of the aggregate surface can be achieved through immersion or coating methods, such as using cement slurry or nanomaterials to form a dense coating layer, thereby improving the surface density and mechanical stability of the aggregate. This preprocessing system can optimize the quality of aggregates at the source and provide a stable foundation for subsequent mix design.

##### 3.1.2 Key Performance Control Methods for Coarse Aggregate

Construct a performance control method centered on "water absorption control pore regulation" to address the issues of high water absorption and pore structure development in recycled coarse aggregates. On the one hand, by pre-wetting treatment and graded control of water absorption rate, the influence of moisture fluctuations in aggregates during the mixing process on the fluidity of the system can be reduced; On the other hand, by combining surface densification treatment to reduce the proportion of open pores, the water migration rate can be lowered, thereby improving the overall stability of the material.

At the level of particle structure, the continuous gradation theory is used to optimize the design of aggregate particle size. By reasonably combining particles of different sizes, the packing density is improved and the porosity is reduced. At the same time, based on the particle stacking model, the proportion relationship between coarse aggregate, fine aggregate, and slurry is coordinated to make the aggregate skeleton structure more stable, reduce the demand for slurry dosage, and improve overall mechanical performance. Through the above multidimensional regulation, the performance transformation of coarse aggregates from "defect dominant" to "structural contribution" can be achieved, providing reliable support for ultra-high performance concrete systems.

#### 3.2 Design Method for Mix Proportion of Ultra High Performance Concrete

##### 3.2.1 Optimization method for cementitious material system

The basic design concept can be represented by an improved compact packing model as follows:

$$\phi = \sum_{i=1}^n V_i \cdot \eta_i \quad (1)$$

( $\phi$ ) is the overall packing density, ( $V_i$ ) is the volume fraction of the (i) - class particles, and ( $\eta_i$ ) is the filling efficiency of the corresponding particles. By adjusting the proportion of different

admixtures, the system can achieve maximum bulk density, thereby reducing porosity and slurry demand.

In terms of activity regulation, the high volcanic ash reactivity of silica fume and the potential hydration characteristics of mineral powder are utilized to achieve the synergistic development of early strength and later strength. By controlling the mass fraction of each admixture to meet:

$$w_{sf} + w_{fa} + w_{sl} \leq 0.5, w_b \quad (2)$$

( $w_{sf}$ ), ( $w_{fa}$ ) and ( $w_{sl}$ ) are the dosages of silica fume, fly ash, and mineral powder, respectively. ( $w_b$ ) is the total amount of cementitious material to avoid excessive admixture leading to insufficient activity and decreased strength.

### 3.2.2 Methods for regulating workability under low water cement ratio

In ultra-high performance concrete systems, the water cement ratio is usually controlled within the range of 0.18-0.25. To ensure good fluidity of the system, it is necessary to finely regulate the dosage and dispersion mechanism of water reducing agents. Based on rheological models, the flowability of the slurry can be described by the Bingham model:

$$\tau = \tau_0 + \mu_p \cdot \dot{\gamma} \quad (3)$$

( $\tau_0$ ) is the yield stress, ( $\mu_p$ ) is the plastic viscosity, and ( $\dot{\gamma}$ ) is the shear rate. The main function of water reducing agents is to reduce ( $\tau_0$ ), thereby improving initial fluidity.

The dosage of water reducing agent is generally controlled according to the mass fraction of cementitious material, and its optimization range can be expressed as:

$$m_{sp} = (1.0\% \sim 2.5\%) \cdot m_b \quad (4)$$

( $m_{sp}$ ) represents the dosage of water reducing agent, and ( $m_b$ ) represents the quality of cementitious material. By gradually adjusting the dosage, the system can avoid segregation and bleeding while meeting the expansion requirements.

### 3.2.3 Method for correcting the mix proportion of coarse aggregate introduction

After introducing coarse aggregates into the UHPC system, it is necessary to modify the traditional mix proportion to maintain a reasonable matching relationship between the slurry and aggregates. Firstly, the aggregate dosage is determined by the volumetric method, and its basic relationship is as follows:

$$V_g + V_m + V_p = 1 \quad (5)$$

( $V_g$ ) is the volume fraction of coarse aggregate, ( $V_m$ ) is the volume fraction of sand, and ( $V_p$ ) is the volume fraction of slurry. Usually, the ( $V_g$ ) is controlled within the range of 0.25~0.40 to ensure the stability of the skeleton structure and not damage the high-density system.

Furthermore, to ensure sufficient wrapping of aggregates, the minimum required amount of slurry can be expressed as:

$$V_p \geq V_{void} + k \cdot V_g \quad (6)$$

( $V_{void}$ ) is the porosity of aggregate stacking, and ( $k$ ) is the wrapping coefficient (usually taken as 0.05~0.10), which is used to ensure that the slurry can form a continuous wrapping layer.

Considering the influence of interface transition zone (ITZ) on mechanical properties, the strength is adjusted by introducing interface correction coefficient:

$$f_c = f_0 \cdot (1 - \alpha \cdot V_{ITZ}) \quad (7)$$

$(f_c)$  is the actual compressive strength,  $(f_0)$  is the ideal strength of a dense system,  $(V_{ITZ})$  is the volume fraction of the interfacial zone, and  $(\alpha)$  is the interfacial weakening coefficient. By reducing the water cement ratio, optimizing the surface properties of aggregates, and increasing the content of active admixtures,  $(V_{ITZ})$  can be effectively reduced and its negative effects can be minimized.

### 3.3 Optimization methods for UHPC preparation process

#### 3.3.1 Mixing process and feeding sequence design

To ensure the uniformity and stability of the ultra-high performance concrete system, a process path combining staged feeding and graded mixing is adopted. Firstly, in the dry mixing stage, cement, mineral admixtures, and fine aggregates are added to the mixer according to the design ratio. The low-speed mixing time is controlled at 60-90 seconds to ensure that each powder material is fully dispersed and forms a uniform matrix; Subsequently, in the early stage of wet mixing, about 70% of the mixing water is added synchronously with the water reducing agent, and the stirring is controlled at a medium speed for 120-180 seconds to promote the initial wetting and dispersion of the cementitious material.

In the later stage of wet mixing, add the remaining mixing water and coarse aggregate in batches (it is recommended to feed them in 2-3 times), and gradually increase the mixing speed to high speed (200-300 r/min), continue stirring for 120-180 seconds, so that the slurry fully wraps around the aggregate particles, avoiding local agglomeration or uneven wrapping. Water reducing agents should be added in sections during the initial and later stages of wet mixing to improve dispersion efficiency and reduce system cohesion resistance.

The uniformity of mixing can be controlled by the degree of uniformity of the slurry distribution per unit volume, and its criterion can be expressed as a discrete coefficient:

$$C_v = \frac{\sigma}{\mu} \quad (8)$$

$(C_v)$  is the uniformity coefficient,  $(\sigma)$  is the standard deviation of local slurry content, and  $(\mu)$  is the average value. When  $(C_v \leq 0.10)$  occurs, it can be considered that the mixture has reached a good and uniform state. By optimizing the mixing time and speed combination, uniform material dispersion and stable structural construction can be achieved.

#### 3.3.2 Optimization of Forming and Compaction Processes

In the molding stage, vibration compaction technology is used for strengthening treatment to reduce internal porosity and improve structural density. The vibration parameters need to be adjusted in conjunction with the flowability of the mixture. Generally, the vibration frequency is controlled at 40-60 Hz and the vibration time is 20-40 seconds to avoid pore residue caused by insufficient vibration or segregation caused by excessive vibration.

The compaction effect of vibration can be evaluated by changes in porosity, and its basic relationship is:

$$n = 1 - \frac{\rho}{\rho_0} \quad (9)$$

$(n)$  is porosity,  $(\rho)$  is the measured density of the specimen, and  $(\rho_0)$  is the theoretical density. By improving vibration efficiency,  $(n)$  is controlled at a lower level (usually less than 5%), thereby enhancing the overall density of the material.

To further suppress pore defects, secondary vibration or slight pressure forming processes can be combined. Performing a short-term secondary vibration (10-15 s) after the initial vibration is completed can help release residual bubbles; At the same time, when conditions permit, a static pressure of 0.2~0.4 MPa is used to improve the tightness of contact between particles. In addition, the height of the mold and the pouring method should be controlled to avoid excessive free fall causing delamination and gas entrapment, and to reduce the probability of defect generation from the source of the process.

### 3.3.3 Optimization methods for maintenance system

The maintenance process has a critical impact on the formation and strength development of UHPC microstructure, and should promote hydration reaction and structural densification through precise control of temperature and humidity conditions. During the initial maintenance stage (0-24 hours), it is advisable to perform closed curing at  $20 \pm 2$  °C, maintaining a relative humidity of not less than 95%, to prevent premature evaporation of moisture from causing plastic shrinkage and microcracks.

In the later stage of maintenance, a combination of room temperature maintenance and hot maintenance can be used. For systems requiring rapid strength development, heat curing treatment can be carried out after demoulding, with the control temperature of 60~90 °C and the duration of 24~48 h, to accelerate the hydration reaction and promote the formation of C-S-H gel. The temperature rise and fall process should be controlled at a rate of  $\leq 10$  °C/h to avoid internal stress concentration caused by excessive temperature differences.

The early structure formation process can be characterized by the degree of hydration, and its development pattern can be expressed as:

$$\alpha(t) = 1 - e^{-kt} \quad (10)$$

( $\alpha(t)$ ) is the degree of hydration at time (t), and (k) is the reaction rate constant. By increasing the maintenance temperature and humidity, (k) can be effectively increased, thereby accelerating the process of structural densification.

## 4. Results and Discussion

### 4.1 Raw Materials and Basic Parameter Settings

The raw materials used in the experiment include pre-treated recycled coarse aggregates, cement, silica fume, mineral powder and other multi-component cementitious material systems. Recycled coarse aggregates are classified into different grades based on the difference in water absorption after treatment, to reflect the influence of their internal pore structure on the performance of concrete. In the mix design, the water cement ratio is controlled within the range of 0.18-0.24, and the dosage of water reducing agent (accounting for 1.2% -2.2% of the cementitious material mass) is adjusted to meet the workability requirements of different systems. The overall mix proportion is calculated using the volume method, and the volume fractions of each component satisfy the total volume conservation relationship, that is, the sum of the volume fractions of coarse aggregate, fine aggregate, and slurry is 1, thereby ensuring the rationality and stability of the system structure.

### 4.2 Mix Proportion Variable Design

In the process of mix design, a multi factor control variable method is used to systematically adjust key parameters. Firstly, using the volume fraction of coarse aggregate as the main variable,

adjust it in stages within the range of 0.25-0.35 to analyze the impact of changes in aggregate skeleton structure on material properties; Secondly, by setting different water cement ratio levels (0.18, 0.21, and 0.24), the relationship between slurry consistency and strength development was examined, and the basic flow performance was maintained by synchronously adjusting the dosage of water reducing agents; At the same time, different combinations of admixture ratios are introduced into the cementitious material system, and multiple composite systems are constructed by changing the dosage levels of silica fume and mineral powder to achieve synergistic regulation of particle filling effect and volcanic ash reaction activity. The variables are configured through grouping and combination to form a comparative mix proportion system.

### 4.3 Preparation and Forming Process Design

All specimens were prepared according to a unified process flow to reduce the impact of human operation differences. Firstly, this article dry mixes cementitious materials with fine aggregates to evenly distribute the powder and form a basic mixing system; Subsequently, this article added some mixing water and water reducing agents for wet mixing, fully wetting the particle surface and forming a preliminary slurry structure; On this basis, this article adds coarse aggregate and residual moisture in batches, and enhances the wrapping effect of the slurry on the aggregate by increasing the mixing speed to ensure overall mixing uniformity. After the mixing is completed, the concrete is poured into the mold layer by layer and compacted through vibration to fully eliminate internal bubbles and reduce porosity. After the molding is completed, immediately cover and moisturize it, and demold it after the specified time to enter the subsequent curing stage.

### 4.4 Setting of Maintenance Conditions

To investigate the influence of different maintenance systems on the development of material properties, two conditions were set up in the experiment: room temperature maintenance and hot maintenance. Under normal temperature curing conditions, the specimen is placed in an environment of  $20 \pm 2$  °C and maintained at a high relative humidity to prevent moisture loss; Under hot curing conditions, the specimen is placed in a constant temperature environment of 80 °C for a certain period of time after demolding to accelerate the hydration reaction process. During the maintenance process, this article strictly controls the rate of temperature change to avoid internal structural damage caused by excessive temperature differences. Meanwhile, this article promotes the generation of hydration products and the development of structural densification of cementitious materials by continuously maintaining suitable humidity conditions.

Table 1 Results of Different Mix Proportion Parameters and Performance Tests

ID	Coarse Aggregate Volume Fraction	Water–Binder Ratio	Silica Fume Content (%)	Slag Content (%)	Superplasticizer (%)	Slump Flow (mm)	T500 (s)
G1	0.25	0.18	15	20	2.2	710	4.8
G2	0.3	0.18	15	20	2.2	685	5.3
G3	0.35	0.18	15	20	2.2	650	6.1
G4	0.3	0.21	15	20	1.8	720	4.5
G5	0.3	0.24	15	20	1.5	735	4.2
G6	0.3	0.21	10	30	1.8	705	4.9
G7	0.3	0.21	20	20	2	690	5.1

According to Table 1, different mix ratio parameters have a significant impact on the workability

of ultra-high performance concrete. Firstly, under the condition of maintaining a water cement ratio of 0.18, as the volume fraction of coarse aggregate increases from 0.25 to 0.35 (G1 → G3), the expansion gradually decreases from 710 mm to 650 mm, and the T500 time increases from 4.8 s to 6.1 s, indicating a decrease in system fluidity and an increase in viscosity. This is mainly due to the increase in the proportion of coarse aggregate, which enhances the friction between particles and limits the development of the flowability of the mixture due to the relatively insufficient wrapping ability of the slurry.

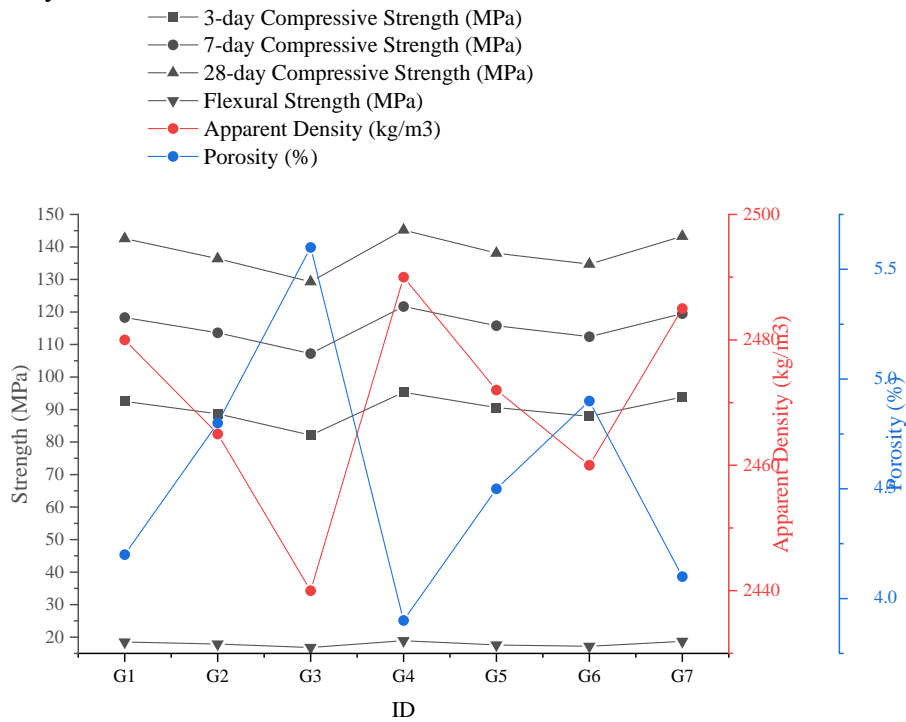


Figure 1. Test results of mechanical properties and structural density

According to Figure 1, different mix ratio parameters have a significant impact on the mechanical properties and structural density of UHPC. Firstly, under the condition of a water cement ratio of 0.18 and constant content of silica fume and mineral powder, as the volume fraction of coarse aggregate increases from 0.25 to 0.35 (G1 → G3), the compressive strength of the material at all ages shows a decreasing trend. The 28 day compressive strength decreases from 142.6 MPa to 129.3 MPa, while the flexural strength decreases from 18.5 MPa to 16.8 MPa. The apparent density decreases from 2480 kg/m<sup>3</sup> to 2440 kg/m<sup>3</sup>, and the porosity increases from 4.2% to 5.6%. This indicates that increasing the amount of coarse aggregate not only enhances the skeleton structure, but also introduces more internal defects due to the relative shortage of slurry and weakening of the interfacial transition zone (ITZ), thereby reducing the overall density and mechanical properties.

## 5. Conclusion

This article focuses on the mix design and preparation process of environmentally friendly coarse aggregate ultra-high performance concrete. Through the pretreatment of recycled coarse aggregate, collaborative optimization of cementitious material system, and systematic control of preparation process, the influence of key parameters on the workability, mechanical properties, and structural density of UHPC is clarified. The results indicate that by optimizing the water cement ratio, coarse aggregate volume fraction, and multi admixture ratio, combined with staged feeding

and efficient mixing processes, the material strength and density can be significantly improved while ensuring good flowability, achieving efficient utilization and performance optimization of environmentally friendly coarse aggregates in UHPC. There are still certain limitations in this study, mainly reflected in the fact that the experimental system is mainly based on indoor conditions, the parameter combination range is limited, and there is a lack of in-depth analysis of the long-term durability and performance evolution laws under complex service environments; In the future, this can be further combined with multi-scale characterization techniques and numerical simulation methods to expand the parameter space and introduce factors affecting the service environment, thereby achieving more comprehensive and accurate performance control and engineering application promotion of environmentally friendly coarse aggregate UHPC.

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