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Deterioration Mechanism of Mechanical Properties of Environmentally Friendly Coarse Aggregate Ultra-High Performance Concrete under High Temperature

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Abstract: Traditional ultra-high performance concrete (UHPC) faces challenges under high temperature conditions, including unclear mechanisms of mechanical property degradation and difficulties in quantitatively describing the performance changes after the introduction of environmentally friendly coarse aggregates. Based on this, this paper takes ultra-high performance concrete with environmentally friendly coarse aggregate as the research object, and constructs an analytical framework of "multi-scale damage mechanism - performance degradation law - constitutive model expression". By introducing a temperature-related damage variable function, a unified degradation model is established to show the changes in strength and elastic modulus with temperature. Furthermore, piecewise functions are used to achieve a refined expression of degradation characteristics in different temperature zones. On this basis, a two-factor experimental system of temperature (20–800°C) and aggregate replacement rate (0%–100%) is designed to systematically analyze the mechanical properties of the material after high temperature. The results show that with increasing temperature, both the compressive strength and elastic modulus of the material exhibit a significant nonlinear decay trend. The established model can effectively reflect the coupling effect of temperature and aggregate replacement rate, and has a good fitting ability for the mechanical property degradation law.

1. Introduction

Against the backdrop of frequent high-temperature disasters and increasing extreme service environments, ultra-high performance concrete (UHPC) is widely used in important engineering structures due to its high strength and high density [1]. However, high temperatures can lead to the decomposition of hydration products in the matrix, deterioration of pore structure, and accumulation of damage in the interface transition zone, resulting in a significant decrease in mechanical properties. At the same time, with the development of green construction concepts, environmentally friendly coarse aggregates are gradually replacing natural aggregates in UHPC systems. However, their internal defects are more numerous and their interfacial properties are weaker, making the damage evolution behavior at high temperatures more complex [2]. Existing research mostly focuses on the analysis of single factors or macroscopic performance testing, lacking a systematic understanding of the degradation mechanism under the coupling effect of "temperature aggregate substitution rate", especially in the quantitative correlation and unified expression of damage evolution and performance degradation [3].

In response to the above issues, this article takes ultra-high performance concrete with environmentally friendly coarse aggregates as the research object, and constructs a multi-scale damage evolution analysis framework around the mechanical performance degradation behavior under high temperature. The mechanism of internal damage is revealed from the aspects of thermal mismatch effect, matrix phase transformation, and interface damage expansion; On this basis, temperature related damage variables are introduced to establish a degradation model for compressive strength and elastic modulus that varies with temperature, and a segmented function is used to achieve a unified expression of the degradation law in different temperature zones. By combining experimental data on the dual factors of temperature and aggregate substitution rate, the model parameters are characterized and the regularity is verified, thereby achieving quantitative description and prediction of the degradation behavior of high-temperature mechanical properties of environmentally friendly coarse aggregate UHPC.

2. Related Works

Existing research has conducted extensive exploration on the high-temperature behavior of ultra-high performance concrete (UHPC) from the perspectives of material composition regulation and performance prediction. In terms of material modification, Luo et al. systematically analyzed the synergistic effect of recycled aggregates (RA) and steel fibers (SF) on the high-temperature performance of UHPC, and pointed out that an increase in temperature would lead to a decrease in density, an increase in porosity, and a degradation of mechanical properties, and the compressive strength would rapidly decrease after reaching its peak at about 400 °C; Meanwhile, increasing the content of steel fibers or reducing the substitution rate of recycled aggregates can alleviate the degradation trend to a certain extent. The mechanism is closely related to the gradual degradation of microstructure with increasing temperature, and a high-temperature stress-strain prediction model has been established based on this [4]. This study indicates that optimizing material composition can improve high-temperature performance to a certain extent, but its effectiveness is still constrained by the temperature dominated damage mechanism.

On this basis, the research has gradually expanded from empirical analysis to data-driven methods. Tabani and Biswas constructed a variety of machine learning models based on large sample data to predict the compressive strength of UHPC. They found that cement and silica fume have a positive contribution to the strength, while limestone powder has a negative correlation. Among them, the XGBoost model has the highest accuracy [5]. Similarly, Katlav and Ergen improved the prediction accuracy by introducing a variety of optimization algorithms to drive the CatBoost model, and used the SHAP method to reveal the key influence of age, fiber and cement dosage [6]. Khan et al. also verified the superiority of XGBoost and integrated models in strength prediction and further revealed the complex interaction relationship between raw materials [7]. Meanwhile, Mao et al. systematically summarized the role of particle size distribution optimization, multi-scale structural control, and machine learning-aided design in improving UHPC performance from the perspective of design methods [8]. Overall, although existing research has made significant progress in performance prediction and material optimization, it is mostly concentrated on room temperature or single working conditions. There is a lack of unified description of the intrinsic coupling relationship between "material composition - damage evolution - mechanical property degradation" under high temperature, especially under the condition of introducing environmentally friendly coarse aggregate, its high temperature degradation law and model expression still need to be studied in depth.

3. Methods

3.1 Multi-scale Damage Evolution Mechanism under High Temperature

3.1.1 Thermal mismatch effect between environmentally friendly coarse aggregate and matrix

Under high temperature conditions, environmentally friendly coarse aggregates and UHPC matrix exhibit significant thermal mismatch effects due to differences in thermal expansion coefficient and thermal conductivity, which is the main cause of early damage. Compared with natural aggregates, recycled or industrial solid waste aggregates have a looser structure, more complex components, and stronger non-uniformity in thermal response. When the temperature rises, the free expansion of the aggregate and matrix is constrained by the interface, which generates additional thermal stress in the interface transition zone and forms stress concentration areas locally. As the temperature further increases, the thermal stress exceeds the bonding strength of the interface, and microcracks first appear in the interface area. The evolution path is "stress accumulation local instability crack initiation". The size, shape, and substitution rate of the aggregate have an amplifying or mitigating effect on the degree of thermal mismatch. The thermal mismatch effect determines the spatial distribution of initial damage and is the driving factor for subsequent damage propagation.

3.1.2 Matrix phase transition and pore structure evolution

At high temperatures, the hydration products of UHPC matrix undergo thermal decomposition reactions, accompanied by continuous evolution of pore structure, which directly weakens the load-bearing capacity. In the medium to low temperature stage, the evaporation of free water and partially adsorbed water causes an increase in capillary pressure, thereby inducing microcracks; After the middle and high temperature zone, the dehydration structure of C-S-H gel collapses, and the decomposition of $Ca\ (OH)_2$ increases the volume of pores, and the material changes from a dense state to a loose state. The evolution of pore structure is manifested by an increase in pore size and enhanced connectivity, which significantly reduces the effective load-bearing area and stiffness of the matrix. Pore expansion provides a path for crack propagation, causing cracks to shift from local expansion to penetration. Matrix phase transformation weakens the strength of the matrix and accelerates the propagation of damage, which is one of the core intrinsic mechanisms of mechanical performance degradation.

3.1.3 Mechanism of Damage Expansion in Interface Transition Zone

The interface transition zone (ITZ), as a weak link between aggregate and matrix, is preferentially damaged at high temperatures. Affected by thermal mismatch stress and degradation of matrix properties, ITZ microcracks first initiate and propagate along the interface, forming an initial crack network. As the temperature increases and the pore structure deteriorates, cracks propagate from the interface to the interior of the matrix, forming a circular crack zone around the aggregate. The path of crack propagation shifts from interface control to matrix control: initially, it propagates along the ITZ, but in the later stage of high temperature, the matrix strength significantly decreases, and cracks are more likely to penetrate the matrix to form through cracks. This process is accompanied by an increase in the number, length, and connectivity of cracks, ultimately leading to macroscopic structural instability and a decrease in load-bearing capacity.

3.2 Main Control Mechanism of Mechanical Performance Degradation

3.2.1 Strength and stiffness attenuation law under temperature classification

Under high temperature conditions, the compressive strength and elastic modulus of environmentally friendly coarse aggregate ultra-high performance concrete exhibit significant nonlinear attenuation, showing a phased evolution law with increasing temperature. The deterioration of mechanical properties can be summarized into three intervals: "slow attenuation accelerated degradation sharp decline", which are expressed as a monotonically decreasing function with temperature.

In the lower temperature range, the internal structure of the material remains relatively intact, with only a slight decrease in strength and stiffness, mainly due to the evaporation of free water and the initial development of micro defects; As the temperature further increases, the hydration products of the matrix gradually decompose, the porosity significantly increases, the material stiffness first shows a rapid decrease, and the strength begins to significantly decline; After entering the high-temperature zone, the interface bonding failure and crack propagation work together, causing the material's load-bearing capacity to rapidly lose, and both strength and elastic modulus show a steep decrease trend.

3.2.2 Coupling effect of aggregate substitution rate and performance degradation

Under the same temperature conditions, the substitution rate of environmentally friendly coarse aggregates has a significant regulatory effect on the deterioration of material mechanical properties, mainly reflected in the initial performance level and high-temperature degradation rate. With the increase of substitution rate, due to the low strength and numerous internal defects of recycled or solid waste aggregates, the initial compressive strength and elastic modulus of the material show a decreasing trend. At the same time, the number of interface transition zones increases, further enhancing the heterogeneity of the overall structure.

Under high-temperature conditions, this heterogeneous structure will intensify the thermal mismatch effect, which will lead to an increase in the concentration of interface stress and accelerate the initiation and propagation of cracks. Specifically, at the same temperature level, the strength retention rate and stiffness retention rate of high replacement rate specimens are lower than those of low replacement rate specimens, and the degradation curve decreases more sharply with increasing temperature.

3.3 Deterioration Constitutive Model and Law Expression

3.3.1 Temperature related damage variables and evolution functions

To quantitatively describe the cumulative degree of internal damage in materials under high temperature, a temperature related damage variable (D (T)) is introduced to characterize the evolution process of materials from intact state to failure state. According to the theory of continuous damage mechanics, the damage variable is defined as:

$$D(T) = 1 - \frac{E(T)}{E_0} \tag{1}$$

(E(T)) is the elastic modulus at temperature (T), and (E_0) is the initial elastic modulus at room temperature. This definition can reflect the development of internal microcracks and the degree of deterioration of pore structure in materials from the perspective of stiffness degradation.

Based on the nonlinear characteristics of damage evolution at high temperatures, an exponential function can be used to describe the damage variables:

$$D(T) = 1 - \exp(-\alpha T^{\beta}) \tag{2}$$

(α) and (β) are parameters related to material composition and aggregate replacement rate. This functional form can effectively characterize the transformation process of damage from slow growth to rapid accumulation with temperature. When the temperature is low, (D(T)) increases slowly; as the temperature rises, the damage variable rapidly approaches 1, reflecting that the material is approaching a state of complete failure.

3.3.2 Construction of Mechanical Property Degradation Model

Based on the definition of the damage variable, a degradation model of the material's mechanical properties with temperature can be further established. For compressive strength $(f_c(T))$ and elastic modulus (E(T)), they can be expressed as:

$$f_c(T) = f_{c0} \cdot (1 - D(T))^{\gamma} \tag{3}$$

$$E(T) = E_0 \cdot (1 - D(T)) \tag{4}$$

(f_{c0}) represents the compressive strength at room temperature, and (γ) is a parameter reflecting the sensitivity of strength to damage. Compared to the linear degradation relationship of the elastic modulus, strength degradation usually exhibits stronger nonlinear characteristics. Therefore, correction using an exponential form can more accurately reflect the actual changing trend.

3.3.3 Unified Expression and Piecewise Function Description of Degradation Laws

To further improve the model's ability to express the degradation characteristics of different temperature ranges, a piecewise function is introduced to uniformly describe the temperature range based on the continuous damage model. According to the material property evolution characteristics, the temperature range can be divided into three typical intervals, and different function forms are used for fitting:

$$\frac{f_c(T)}{f_{c0}} = \begin{cases} 1 - a_1 T, & T \le T_1 \\ \exp(-a_2 T), & T_1 < T \le T_2 \\ a_3 \exp(-a_4 T), & T > T_2 \end{cases} \tag{5}$$

$$\frac{E(T)}{E_0} = \begin{cases} 1 - b_1 T, & T \le T_1 \\ \exp(-b_2 T), & T_1 < T \le T_2 \\ b_3 \exp(-b_4 T), & T > T_2 \end{cases} \tag{6}$$

(T_1) and (T_2) are characteristic temperature points, and (a_i) and (b_i) are fitting parameters. This piecewise function can describe the linear slow decay in the low-temperature region, the accelerated degradation in the mid-temperature region, and the sharp decline in the high-temperature region, respectively.

4. Results and Discussion

4.1 Raw Materials and Mix Design

The experiment used ultra-high performance concrete (UHPC) as the matrix system. The cementitious material consisted of cement, mineral admixtures, and a high-efficiency water-reducing agent. Quartz sand was used as the fine aggregate, and natural aggregate and environmentally friendly coarse aggregate (such as recycled aggregate or industrial solid waste aggregate) were used as coarse aggregates. To control variables, the water-cement ratio and the amount of cementitious material were kept constant; only the coarse aggregate replacement rate was adjusted.

The substitution rate of coarse aggregates is set at multiple levels (such as 0%, 30%, 60%, 100%) to characterize the impact of the degree of introduction of environmentally friendly aggregates on material properties. On the premise of ensuring consistent workability, each group of specimens controls their flow ability by adjusting the dosage of additives, making different mix proportions comparable.

4.2 Preparation and Grouping Plan for Test Specimens

The test specimens are in two forms: standard cubes (such as 100 mm × 100 mm × 100 mm) and prisms (such as 100 mm × 100 mm × 300 mm), which are used for compressive strength and elastic modulus testing, respectively. All specimens are prepared using a uniform mixing process, and after pouring, they are subjected to standard curing until the specified age.

Design grouping based on the principle of "temperature substitution rate" dual factor combination. The temperature level is set to normal temperature and multiple high temperature levels (such as 200 ℃, 400 ℃, 600 ℃, 800 ℃), combined with different substitution rates to form a complete test matrix. Each group should have no less than 3 parallel specimens to reduce the influence of discreteness.

4.3 High Temperature Treatment System

After reaching the specified age, the specimen is subjected to high-temperature treatment and temperature controlled loading is carried out using an electric heating furnace. The heating process adopts a staged uniform heating method (such as 5 ℃/min) to reduce the additional thermal stress caused by temperature gradient. After reaching the target temperature, maintain a constant temperature for a period of time (such as 1-2 hours) to ensure that the internal temperature field of the specimen tends to stabilize.

After the high-temperature treatment is completed, the specimen is naturally cooled to room temperature in the furnace to avoid additional damage caused by rapid cooling. The entire process strictly controls temperature errors and records temperature change curves to ensure experimental consistency.

4.4 Mechanical Performance Testing Methods

The specimens after high-temperature treatment can be tested for compressive strength and elastic modulus. The compressive strength test adopts a standard pressure testing machine, which is loaded at a constant loading rate until failure, records the peak load, and calculates the strength value.

The elastic modulus test adopts axial loading method, and the stress-strain relationship curve is obtained by installing displacement or strain gauges, and the elastic modulus of the material is calculated during the elastic stage. It controls the loading rate and alignment conditions during the testing process to reduce experimental errors.

4.5 Data Processing and Parameter Extraction Methods

The experiment conducted statistical analysis on the experimental data of each group, using the average value as the representative value, and calculated the standard deviation to assess the dispersion of the data. On this basis, this article extracts the strength retention rate and elastic modulus retention rate under different temperature and substitution rate conditions. By normalizing the test results, convert them into dimensionless forms (such as $(f_c(T)/f_{c0})$, $(E(T)/E_0)$ for subsequent model parameter fitting and pattern analysis. Fit the data curve, determine the model parameters, and evaluate the fitting accuracy and applicability.

Table 1 Compressive strength and retention rate at different temperatures and aggregate substitution rates

Temperature (℃)	Replacement Rate (%)	Compressive Strength (MPa)	Strength Retention Ratio
20	0	152.3	1
200	0	138.7	0.91
400	0	112.5	0.74
600	0	78.2	0.51
800	0	42.6	0.28
20	50	138.9	1
200	50	120.4	0.87
400	50	92.3	0.66
600	50	60.7	0.44
800	50	28.9	0.21
20	100	126.7	1
200	100	104.6	0.83
400	100	75.8	0.6
600	100	46.3	0.37
800	100	19.5	0.15

As shown in Table 1, under different aggregate substitution rates, the compressive strength exhibits a significant nonlinear decay trend with increasing temperature. For the natural aggregate group (0% substitution rate), the compressive strength gradually decreased from 152.3 MPa at room temperature to 42.6 MPa at 800 ℃, and the strength retention rate decreased to 0.28, indicating that high temperature has a significant weakening effect on the bearing capacity of UHPC. From the perspective of the magnitude of the change, the strength decreases relatively slowly within 200 ℃ (with a retention rate still higher than 0.90), while entering an accelerated decay stage after 400 ℃, with a significant drop in strength at 600 ℃ and 800 ℃, reflecting typical temperature sensitivity enhancement characteristics.

In the comparison of different substitution rates, the introduction of environmentally friendly coarse aggregates further amplifies the high-temperature degradation effect. Taking a 50% substitution rate as an example, its strength at room temperature is lower than that of the control group, and the strength retention rate decreases at all temperature stages; When the substitution rate increases to 100%, this trend becomes more significant, with a strength of only 19.5 MPa at 800 ℃, corresponding to a retention rate of 0.15, which is about 46% lower than the natural aggregate group. At the same time, it can be observed that the higher the substitution rate, the steeper the decrease curve of strength with increasing temperature, indicating a significant increase in the sensitivity of the material to temperature changes.

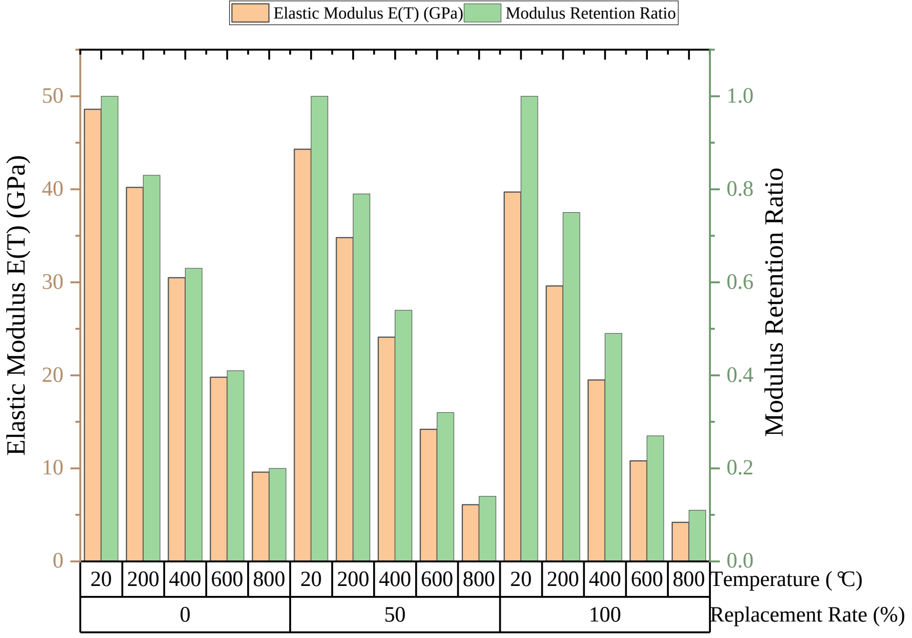

Figure 1. Elastic modulus and retention rate at different temperatures and aggregate substitution rates

As shown in Figure 1, under different aggregate substitution rates, the elastic modulus exhibits more significant nonlinear attenuation characteristics with increasing temperature. Taking the natural aggregate group as an example, the elastic modulus decreased from 48.6 GPa at room temperature to 9.6 GPa at 800 ℃, corresponding to a retention rate of only 0.20, with an overall decrease of over 80%. Compared with the trend of compressive strength changes, the elastic modulus has shown a significant decrease in the 200 ℃ stage (with a retention rate of 0.83), and enters a rapid decay range after 400 ℃. The temperature stage of 600 ℃ and above shows an approximately exponential decrease, indicating that material stiffness is more sensitive to temperature changes.

The comparison of different substitution rates shows that the introduction of environmentally friendly coarse aggregates significantly exacerbates the degradation of elastic modulus. When the substitution rate increases from 0% to 100%, the elastic modulus at room temperature decreases from 48.6 GPa to 39.7 GPa, and the initial stiffness has significantly decreased; Under high temperature conditions, the difference further widens. At 800 ℃, the moduli decrease to 9.6 GPa, 6.1 GPa, and 4.2 GPa, respectively, and the corresponding retention rate decreases from 0.20 to 0.11, with a significant increase in attenuation amplitude. At the same time, it can be seen that the higher the substitution rate, the steeper the modulus attenuation curve, indicating that the internal structure of the material is more sensitive to thermal effects.

5. Conclusion

This article focuses on the mechanical performance degradation behavior of environmentally friendly coarse aggregate ultra-high performance concrete under high temperature, and constructs a unified analysis framework of "damage mechanism performance degradation constitutive model". Research has shown that materials exhibit significant nonlinear degradation characteristics in high-temperature environments, with compressive strength and elastic modulus continuously decreasing with increasing temperature. Among them, the elastic modulus is more sensitive to temperature and exhibits characteristics of strength degradation before strength degradation; The introduction of environmentally friendly coarse aggregates reduces initial performance, but further amplifies thermal mismatch effects and interface damage under high temperature conditions, significantly exacerbating the rate of performance degradation. By introducing temperature related damage variables, a degradation model for strength and stiffness was established, and a unified expression of the degradation law in different temperature zones was achieved by combining segmented functions. The model can better reflect the coupling effect of temperature and substitution rate and their impact on mechanical properties. However, this study still has certain limitations, such as not considering the effects of multiple high-temperature cycles and differences in cooling paths on material properties, further deepening the quantitative characterization of microstructure evolution, and the dependence of model parameters on specific material systems. Universality still needs to be further verified. Future research can start from multi-field coupling effects (such as thermal mechanical water), combined with microscopic testing and numerical simulation methods, to improve the damage evolution mechanism and model parameter calibration system. At the same time, it can be extended to practical engineering scale applications to enhance the predictive ability and engineering applicability of the model in complex service environments.

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