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Research Progress and Prospects on the Performance of Recycled Aggregate Concrete under High Temperature

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Abstract: This paper systematically reviews domestic and international research literature on the performance evolution of recycled aggregate concrete under high-temperature conditions in recent years. It summarizes the influence patterns of factors such as temperature, aggregate replacement rate, and fiber admixtures on the high-temperature performance of recycled aggregate concrete from the perspectives of macroscopic mechanical properties, microscopic degradation mechanisms, and performance improvement techniques. The analysis indicates that the interfacial transition zone is a weak link in the high-temperature damage of recycled aggregate concrete; its high-temperature resistance can be effectively enhanced through methods such as fiber reinforcement and alkali-activated cementitious systems.

Keywords: High-temperature exposure; Recycled aggregate; Performance

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1. Introduction

With the urgent need for global resource utilization of construction waste and sustainable development in the concrete industry, research and application of recycled aggregate concrete are becoming increasingly widespread [1]. However, compared to natural aggregate concrete, recycled aggregate exhibits high porosity, low strength, and high-water absorption due to the presence of adhered old cement mortar. These inherent defects raise significant concerns about the mechanical properties and durability of recycled aggregate concrete under complex conditions such as high temperatures and fires [2]. Investigating the performance degradation patterns and mechanisms of recycled aggregate concrete under high temperatures and developing effective reinforcement techniques are crucial for evaluating and enhancing the safety and fire resistance of recycled aggregate concrete structures. This paper aims to systematically review research achievements in this field in recent years, providing references for subsequent research and practice.

2. The influence pattern of high temperature on the macroscopic mechanical properties of recycled aggregate concrete

Macroscopic mechanical properties are central to evaluating the safety of concrete structures. Under high temperatures, parameters such as the compressive strength, tensile strength, and elastic modulus of recycled aggregate concrete exhibit significant deterioration characteristics with variations in temperature and aggregate replacement rate, and are regulated by heating and cooling regimes. The deterioration pattern differs from that of natural aggregate concrete [3].

2.1. High-temperature evolution characteristics of compressive strength

At low temperatures, water evaporation promotes densification of the cement paste, compensating for defects in the recycled aggregates. After reaching supercritical temperatures, strength decreases significantly, and the structure is completely destroyed under high temperatures. The higher the replacement rate of recycled aggregates, the more pronounced the deterioration. High replacement rates tend to form interfacial defects, accelerating strength loss and increasing brittleness. The higher the concrete strength grade, the relatively better the load-bearing capacity and stiffness after exposure to high temperatures [4].

2.2. Changes in tensile strength and bonding properties

Tensile strength is more sensitive to temperature, continuously decreasing with increasing temperature. The low-temperature enhancement effect is not significant, and the decrease in tensile strength at high temperatures is much greater than that of compressive strength. The core reasons are the initiation of micro-cracks in the interfacial transition zone and the weakening of the bond between new and old mortar. An increase in the replacement rate exacerbates deterioration [5].

Under high temperatures, the bonding properties between steel reinforcement and concrete also deteriorate, and the degree of deterioration decreases with increasing cover thickness [6,7].

The rise in temperature reduces the bond strength, and the rate of decline accelerates after high temperatures, which stems from the weakening of the matrix's gripping force and the thickening of the oxide film on the steel bars. The influence of the substitution rate is complex; at low substitution rates, the deterioration is close to that of natural aggregate concrete, while at high substitution rates, the deterioration is more pronounced, with the failure mode shifting from bond failure to splitting failure and increased brittleness [8,9].

Macroscopic mechanical properties are core indicators for assessing the load-bearing capacity and safety of concrete structures. Under high temperatures, the mechanical parameters of recycled aggregate concrete, such as compressive strength, tensile strength, and elastic modulus, exhibit significant evolutionary characteristics with increasing temperature and changes in aggregate substitution rates. These properties are also regulated by factors such as heating methods and cooling regimes, with their deterioration patterns differing from those of natural aggregate concrete [10].

2.3. Response of elastic modulus and deformation performance

The elastic modulus is a core parameter reflecting the stiffness of concrete. Under high temperatures, the elastic modulus of recycled aggregate concrete continuously decreases with increasing temperature, and the rate of decline is faster than that of compressive strength [11]. At room temperature, the elastic modulus of recycled aggregate concrete is already lower than that of natural aggregate concrete due to the high porosity of recycled aggregates and the weak interfacial transition zone, which makes internal microcracks more prone to develop under stress [12]. As the temperature rises, the hydration products of the cement paste decompose, pores increase, and microcracks expand, further reducing the elastic modulus until the material loses its stiffness.

The substitution rate of recycled aggregates has a significant impact on the elastic modulus, showing a monotonically decreasing trend with increasing substitution rates [13]. The type of fine aggregate can also affect the rate of deterioration. When both recycled coarse and fine aggregates are incorporated, the elastic modulus deteriorates faster than when only coarse or fine aggregate is incorporated separately [14]. In terms of deformation performance, the peak strain and Poisson's ratio at high temperatures exhibit a trend of "first decreasing and then increasing", with a distinct critical temperature: prior to the critical temperature, they decrease slightly with increasing temperature, which is related to the further hydration and densification of the cement paste; after the critical temperature, they increase significantly, with the rate of increase rising with temperature, due to the extensive expansion of internal micro-cracks and enhanced plastic deformation capacity. An increase in the replacement rate of recycled aggregate leads to a further increase in peak strain, with the peak point of the stress-strain curve shifting downward and to the right, and the curve becoming flatter, indicating a degradation in ductility and an increase in brittleness.

3. Microscopic deterioration mechanism of recycled aggregate concrete at high temperatures

The deterioration of the macroscopic mechanical properties of recycled aggregate concrete at high temperatures stems from internal microstructural damage and changes in chemical composition. The weak interface transition zone (ITZ) is the core reason why its high-temperature performance is inferior to that of natural aggregate concrete. Clarifying the deterioration mechanism is crucial for developing improvement technologies.

3.1. Characteristics of microstructural evolution

The microstructure of recycled aggregate concrete is complex, consisting of natural aggregates, old and new cement mortars, and multiple interface transition zones (ITZs), with the ITZs being the weak links [15]. At room temperature, there are two types of ITZs, both characterized by high porosity, loose structure, and numerous micro-cracks. The structural evolution at high temperatures exhibits temperature dependence: At low temperatures, only water evaporates, and the interface integrity is largely maintained. At medium temperatures, hydration products decompose, interface cracks initiate and propagate, bond strength weakens, and structural continuity is disrupted. At high temperatures, the interface completely detaches, forming a network of through-cracks, and the material integrity is lost. Studies have confirmed that after exposure to high temperatures, there is a significant increase in internal micro-cracks and pores, which propagate along the interfaces. The higher the replacement rate of recycled aggregates, the more pronounced the deterioration becomes [16].

3.2. Chemical and physical deterioration mechanisms

Microscopic deterioration is the result of the synergistic effects of chemical and physical degradation. Chemical deterioration manifests as the gradual decomposition of cement hydration products with increasing temperature, resulting in volume changes and internal stresses that accelerate the development of micro-cracks [17]. Physical deterioration encompasses three aspects: First, water evaporation generates vapor pressure, leading to cracks and spalling due to the obstruction of interface drainage. Second, differences in the thermal expansion coefficients of various components and internal-external temperature gradients generate thermal stresses, triggering interface cracks. Third, the mismatch in thermal expansion among the internal components of recycled aggregates produces additional stresses, exacerbating interface damage, which is a significant characteristic of its physical deterioration.

The deterioration of the macroscopic mechanical properties of recycled aggregate concrete at high temperatures stems from internal microstructural damage and changes in chemical composition. The weakness of the interfacial transition zone is the core reason why its high-temperature performance is inferior to that of natural aggregate concrete [18]. A thorough understanding of the microscopic deterioration mechanisms is of great significance for the development of targeted improvement technologies.

3.3. Application of microscopic characterization techniques

Microscopic characterization techniques serve as the core support for revealing the mechanism of high-temperature deterioration. Scanning electron microscopy (SEM) allows for the direct observation of internal pores, cracks, and interfacial states, and when combined with energy-dispersive spectroscopy (EDS), it enables the quantitative analysis of elemental composition [19]. X-ray diffraction (XRD) can clarify phase changes and verify the decomposition process of hydration products. Mercury intrusion porosimetry (MIP) quantitatively characterizes the deterioration of pore structure and reflects its correlation with macroscopic properties. Digital image correlation (DIC) provides real-time monitoring of strain and crack propagation, while nuclear magnetic resonance (NMR) precisely characterizes moisture states. The combined application of these techniques significantly enhances the depth of understanding regarding deterioration mechanisms.

4. Techniques for improving high-temperature performance of recycled aggregate concrete

In response to the high-temperature performance deficiencies of recycled aggregate concrete, various improvement techniques have been developed in academia, primarily focusing on fiber reinforcement and cementitious system optimization, among others. These techniques aim to compensate for the inherent defects of recycled aggregates from multiple dimensions and enhance their high-temperature resistance.

4.1. Fiber reinforcement techniques

This technique involves the incorporation of fibers to hinder the development of microcracks at high temperatures, improve ductility and crack resistance, and reduce spalling. Different types of fibers commonly used have varying focuses in their effects [20]. Steel fibers, which are highly resistant to high temperatures and possess high strength, achieve reinforcement across the entire temperature range by bridging cracks and enhancing interfacial bonding. However, their dosage must be controlled to avoid a decline in workability. Polypropylene fibers have low strength at room temperature and melt at high temperatures, forming pore channels that facilitate the escape of water vapor and reduce vapor pressure, primarily enhancing spalling resistance. They are often mixed with steel fibers to balance room-temperature performance and high-temperature spalling resistance. Inorganic fibers such as basalt fibers and carbon fibers can improve high-temperature performance; however, the former is costly, while the latter has the potential for health monitoring, making it a future research focus [21].

4.2. Optimization of the cementitious system

The cementitious system is the core factor influencing high-temperature performance, with optimization primarily achieved through the addition of mineral admixtures and the use of alkali-activated systems. Mineral admixtures (such as fly ash and slag) generate stable hydration products through secondary reactions, improving the microstructure [22]. Metakaolin exhibits significant high-temperature resistance but is costly, making it suitable for special environments. Alkali-activated cementitious systems are a novel green approach that utilizes alkaline activators to stimulate industrial waste slag, forming stable, high-strength hydration products. These systems demonstrate far superior high-temperature stability compared to traditional systems, maintaining good load-bearing capacity under high temperatures while reducing cement usage and carbon emissions, aligning with sustainable development goals and representing an important future direction.

4.3. Pretreatment methods for recycled aggregates

The inherent defects of recycled aggregates, such as high porosity and high-water absorption, are the root causes of their poor high-temperature performance. Pretreatment can enhance high-temperature resistance from the source, primarily through physical and chemical modification methods. Physical modification encompasses particle shaping, high-temperature calcination, and pre-wetting treatment: particle shaping removes aged mortar from the surface through mechanical means, optimizing the gradation and morphology; high-temperature calcination can close internal micro-cracks and densify the aged mortar, with enhanced effects when combined with particle shaping; pre-wetting treatment reduces the absorption of moisture from fresh paste by aggregates, improving interfacial bonding, but requires humidity control to avoid exacerbating damage from high-temperature steam pressure. Chemical modification strengthens interfacial bonding by applying reagents such as silane coupling agents and cement pastes, among which silane coupling agents can form a composite film to enhance high-temperature stability, significantly increasing the compressive strength retention rate at high temperatures and reducing interfacial cracks.

4.4. Optimization of mix proportion design

Rational mix proportion design can improve the internal structure and enhance high-temperature performance, primarily focusing on optimizing the water-binder ratio, adjusting aggregate gradation, and controlling the replacement rate of recycled aggregates [23]. The water-binder ratio must balance workability and high-temperature performance, as excessive ratios can increase porosity and reduce stability, necessitating experimental determination of the optimal value. Adjusting aggregate gradation using continuous gradation can enhance compactness, while incorporating lightweight aggregates such as vitrified microspheres can impede heat transfer, release steam pressure, and enhance fire resistance. The replacement rate of recycled aggregates is negatively correlated with high-temperature performance, with an optimal range existing where both room-temperature and high-temperature performances approach those of natural aggregate concrete; high replacement rates result in significant deterioration, requiring strict control in projects with high-temperature requirements, while general projects can appropriately increase the rate but require complementary reinforcement measures.

5. Conclusion

Recycled aggregate concrete, as the core technology for the resource utilization of construction waste, holds significant importance in promoting the sustainable development of the concrete industry. However, the issue of performance degradation under high-temperature environments restricts its large-scale engineering application. Although current research has made some progress, there are still many shortcomings. Future research can focus on the following areas: the law of performance degradation under the coupling effect of multiple factors, delving into the performance evolution under the coupling effect of temperature-load-erosive media to better align with actual engineering environments; performance restoration technologies after high-temperature exposure, developing efficient and cost-effective restoration materials and processes to extend the service life of structures; meso-macro coupled numerical simulation and prediction models to achieve accurate prediction of high-temperature performance; and the integration of engineering application technologies, formulating design codes and construction guidelines to promote large-scale application. With further research and technological innovation, the high-temperature resistance of recycled aggregate concrete will continue to improve, and its application scope will expand, providing strong support for the resource utilization of construction waste and the green and low-carbon development of the construction industry.

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