

The Application of Recycled Aggregate Concrete in Sustainable Civil Engineering

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Abstract: As the global construction industry accelerates its transformation toward low-carbon and circular development, the demand for eco-friendly and renewable construction materials has risen sharply. Recycled aggregate concrete (RAC), which is manufactured by replacing natural coarse and fine aggregates with crushed construction and demolition (C&D) waste, has become one of the most promising sustainable alternatives to conventional ordinary concrete. This paper systematically explores the fundamental material characteristics, structural mechanical performance, practical engineering application scenarios, and comprehensive environmental benefits of recycled aggregate concrete. Meanwhile, it comprehensively analyzes the core technical bottlenecks restricting its large-scale promotion, including unstable material quality, decreased mechanical strength, and poor durability performance caused by residual adhered mortar on recycled aggregates. This study systematically summarizes three mainstream performance enhancement technical systems: optimized concrete mix proportion design, physical and chemical modification treatment of recycled aggregates, and innovative advanced curing and processing technologies. Typical engineering case studies are supplemented to elaborate on the practical application effects of RAC in building structural components, road pavement engineering, and non-load-bearing precast concrete members. Furthermore, the industrial development barriers such as imperfect unified industry standards, insufficient construction experience, and low market recognition are discussed in depth, and targeted suggestions for future academic research and engineering popularization are proposed. The research results of this paper clarify the application potential and development value of RAC, aiming to provide theoretical support and technical reference for the large-scale application of recycled aggregate concrete and further promote the high-quality sustainable development of modern civil engineering.

Keywords: Recycled aggregate concrete, sustainable construction, material properties, structural performance, environmental benefits, performance optimization.

1. Introduction

The civil engineering and construction industry is the backbone of national economic development, yet it is also a typical industry with high resource consumption and high carbon emission characteristics. According to authoritative statistical data from the International Energy Agency, the global construction and building sector consumes more than 40% of terrestrial natural resources annually, and traditional concrete production alone accounts for approximately 8% of global anthropogenic carbon dioxide emissions, bringing huge pressure on global ecological environment governance and carbon neutrality goals [1]. Natural aggregate, as the core raw material of traditional concrete, relies on long-term mountain quarrying and river sand mining. Long-term uncontrolled exploitation of natural aggregates not only causes severe river channel erosion, mountain vegetation destruction, and geological stability damage but also leads to the gradual depletion of non-renewable mineral resources, which restricts the long-term sustainable development of the construction industry.

With the rapid advancement of urban renewal, old community reconstruction, and infrastructure upgrading projects in various countries, a huge amount of construction and demolition waste is generated every year. Most C&D waste is randomly landfilled or stacked in open air, occupying valuable land resources and causing secondary environmental pollution such as soil salinization and surface water pollution [2]. Under the background of global circular economy development and green building policies, the resource utilization of construction waste has become an inevitable

development trend. Recycled aggregate concrete (RAC) realizes the resource recycling of waste concrete and brick masonry by crushing, screening, and grading waste construction materials to replace natural aggregates in concrete preparation. This technology can effectively divert massive construction waste from landfills, reduce the exploitation of natural raw materials, and cut down the carbon footprint of concrete engineering, which has remarkable ecological and economic benefits.

Nevertheless, compared with traditional natural aggregate concrete, recycled aggregate concrete has inherent material defects that limit its widespread industrial application. The surface of recycled aggregates is covered with a layer of residual old cement mortar formed in the original service stage. The porous and loose structure of adhered mortar significantly increases the water absorption rate of aggregates, while microcracks generated during the crushing process further deteriorate the internal structural integrity of recycled aggregates [3]. These inherent defects lead to unstable working performance of fresh RAC, decreased mechanical strength of hardened concrete, and poor long-term durability. At present, the application scope of RAC is still limited, and there are widespread problems such as inconsistent quality control standards, immature construction technology, and insufficient industry popularization awareness.

Based on the above background, this paper systematically sorts out the basic physical and mechanical properties and durability characteristics of recycled aggregate concrete, summarizes mature technical methods for RAC performance improvement, analyzes typical engineering application scenarios, and discusses the environmental advantages and

existing development obstacles of RAC. The purpose is to comprehensively demonstrate the application value of RAC in sustainable civil engineering and put forward feasible development suggestions for its future industrial promotion.

2. Material Properties of Recycled Aggregate Concrete

The fundamental difference between recycled aggregates and natural aggregates lies in the residual adhered mortar and internal micro-defects formed during service and crushing, which fundamentally change the physical, mechanical, and durability properties of recycled aggregate concrete. The performance differences are mainly reflected in workability of fresh concrete, mechanical strength of hardened concrete, and long-term structural durability.

In terms of basic physical properties, natural aggregates have dense internal structure and smooth surface, with a water absorption rate stably controlled below 2% [4]. In contrast, the porous structure of residual mortar on recycled aggregates greatly improves the water absorption capacity, with the water absorption rate ranging from 3% to 12% depending on the waste concrete strength grade, crushing fineness, and mortar residual content. Higher recycled aggregate replacement ratio corresponds to higher overall water demand of concrete mixture. In the actual mixing process, recycled aggregates will absorb a large amount of free water in the mixture, which easily leads to insufficient slump of fresh concrete, poor fluidity and workability, and affects subsequent pumping and pouring construction quality. Therefore, the traditional concrete mix design method is no longer applicable to RAC, and targeted adjustment of water consumption and admixture dosage is required.

In terms of mechanical properties, the compressive strength, tensile strength, and elastic modulus of RAC are all negatively correlated with the replacement rate of recycled aggregates [5]. When the recycled aggregate replacement rate reaches 100%, the 28-day compressive strength of concrete decreases by 10% to 30% compared with conventional concrete. The strength attenuation mechanism is mainly divided into two aspects: first, the residual mortar on the surface of recycled aggregates has low strength and high porosity, which forms weak structural interfaces inside concrete; second, microcracks generated during aggregate crushing will expand and penetrate under external load, accelerating structural damage [6]. In addition, the bonding performance between recycled aggregates and new cement mortar is weaker than that of natural aggregates, resulting in poor interface transition zone performance, which further reduces the overall mechanical properties of RAC. The elastic modulus of RAC is also significantly lower than that of ordinary concrete, leading to larger deformation and creep strain under long-term load.

Durability is a key index restricting the service life of RAC structures. The high porosity of RAC increases the permeability of gas and liquid in concrete. On the one hand, carbon dioxide in the air easily penetrates into the concrete interior, accelerating the carbonation reaction of cement mortar, increasing the carbonation depth of concrete, and weakening the protective effect on steel bars [7]. On the other hand, in coastal and de-icing salt environment, chloride ions are more likely to invade the structure, causing steel bar corrosion, volume expansion, and concrete cracking damage. In terms of frost resistance, the internal porous structure of

RAC will absorb a large amount of water. Under freeze-thaw cycle conditions, water freezes and expands to generate expansion stress, leading to structural peeling and cracking. Research shows that the freeze-thaw damage degree of full-replacement RAC is more than twice that of ordinary concrete, and auxiliary air entrainment measures must be adopted in cold regions engineering [8].

3. Methods to Enhance RAC Performance

Aiming at the inherent performance defects of recycled aggregate concrete, domestic and foreign scholars have developed a variety of targeted improvement technologies after years of experimental research and engineering exploration, mainly including mix design optimization, aggregate modification treatment, and advanced curing processing technology, which can effectively compensate for the performance deficiency of RAC and realize performance restoration and improvement.

3.1. Mix Design Optimization

Traditional fixed water-cement ratio mix design cannot adapt to the high water absorption characteristics of recycled aggregates. Optimizing the mix proportion is the most convenient and efficient technical means to improve RAC performance in engineering practice. The core optimization idea is to make up for the performance defects caused by recycled aggregate defects through scientific proportion collocation and functional admixtures.

Supplementary cementitious materials (SCMs) such as fly ash, mineral slag powder, and silica fume are widely used in RAC modification [9]. These industrial solid waste powders have good pozzolanic activity, which can react with cement hydration products to generate dense calcium silicate hydrate gel, fill the internal pores of concrete, optimize the pore structure, and significantly improve the compactness and interface bonding strength of RAC. Among them, silica fume has fine particle size and high activity, which can effectively repair the weak interface transition zone between recycled aggregate and new mortar; fly ash can improve the fluidity of fresh concrete and reduce the internal hydration heat of concrete. In addition, adjusting the effective water-cement ratio according to the actual water absorption of recycled aggregates and adding high-efficiency polycarboxylate superplasticizers can offset the water loss caused by aggregate water absorption, ensure the workability of fresh concrete, and reduce the shrinkage deformation of hardened concrete [10].

3.2. Aggregate Treatment

Aggregate modification treatment directly eliminates the inherent defects of recycled aggregates from the source, which is the fundamental way to improve RAC performance. At present, physical and chemical treatment technologies are widely used in engineering.

Physical mechanical treatment mainly includes secondary crushing, surface scrubbing, and screening grading [11]. The secondary crushing technology can peel off most of the loose residual mortar on the aggregate surface, reduce the aggregate water absorption rate, and optimize the aggregate particle shape and gradation; surface scrubbing removes fine powder and loose mortar attached to the surface, improving the surface roughness and bonding performance of aggregates.

Chemical treatment is to modify the surface of recycled aggregates through chemical solutions. Common treatment agents include dilute acid solution and silica fume slurry [12]. The dilute acid solution can corrode and remove loose residual mortar on the aggregate surface; silica fume impregnation treatment can form a dense active layer on the aggregate surface, enhance the chemical bonding force between aggregate and new cement mortar, and effectively improve the interface structural performance of RAC.

3.3. Advanced Processing

With the development of green building technology, advanced curing and processing technologies have been gradually applied to RAC performance improvement, realizing the overall performance upgrading of concrete.

Carbonation curing technology is an efficient low-carbon modification method [13]. By exposing fresh RAC to carbon dioxide environment, the calcium hydroxide in cement hydration products reacts with CO_2 to generate dense calcium carbonate crystals, which fill the internal pores and microcracks of concrete, significantly improving the compactness, compressive strength and carbonation resistance of RAC. Microbial carbonate precipitation technology uses microbial metabolic reaction to induce calcium carbonate deposition in the concrete matrix [14], which can automatically repair internal microcracks, reduce structural porosity, and improve the long-term durability of RAC, with the advantages of environmental protection and no secondary pollution.

4. Applications of RAC in Civil Engineering

After years of technical optimization and engineering verification, recycled aggregate concrete has formed mature application systems in building structures, road infrastructure, and precast component engineering, and its application scope is gradually expanding from non-structural components to medium-load structural components.

4.1. Structural Applications

With the continuous improvement of RAC performance optimization technology, RAC can meet the load-bearing requirements of low and medium-rise building structures under reasonable mix design and aggregate replacement ratio control. Engineering practice shows that when the recycled aggregate replacement rate is controlled within 50%, the mechanical strength and structural stability of RAC can fully meet the design specifications of ordinary civil buildings [15]. A typical residential reconstruction project in Germany adopted 30% recycled coarse aggregate replacement technology. Through mix proportion optimization and carbonation curing treatment, the compressive strength, flexural strength and structural durability of the on-site poured RAC floor beams and columns were basically consistent with traditional concrete, realizing safe and stable operation of the building structure [16]. At present, RAC has been successfully applied to frame beams, floor slabs, bearing walls and other structural components of low-rise residential buildings, office buildings and public facilities, with good structural safety and economic benefits.

4.2. Road Pavements

Road base and sub-base structures have low requirements

for concrete tensile strength and frost resistance, which are the most extensive application fields of RAC. The base layer mainly bears vertical road load and disperses pavement pressure, and recycled aggregate concrete with medium and low strength can fully meet the engineering design requirements. The Netherlands, as a pioneer in construction waste resource utilization, has widely applied RAC to urban bicycle lanes, community low-traffic roads and municipal road base reconstruction projects [17]. The engineering monitoring results show that RAC road base has good compactness and bearing stability, no obvious cracking and settlement damage after long-term service, and the project construction cost is reduced by 15%–20% compared with traditional concrete, while greatly reducing construction waste landfill volume and natural aggregate consumption.

4.3. Non-Load-Bearing Components

Non-load-bearing concrete components have the lowest performance requirements and are the earliest and most mature application scenarios of RAC in engineering. Partition wall panels, pavement bricks, curb stones, landscape precast blocks and other components do not bear structural load, and only need to meet the basic hardness, wear resistance and dimensional stability requirements [18]. Many countries have realized the standardized and industrialized production of RAC precast blocks. A large number of municipal landscape projects and residential community renovation projects adopt RAC pavement bricks and curb stones, which not only meet the functional use requirements but also effectively consume construction waste, promote the closed-loop recycling of construction resources, and conform to the development concept of circular economy.

5. Environmental Benefits and Adoption Barriers

Recycled aggregate concrete has outstanding environmental and ecological advantages compared with traditional concrete in the whole life cycle. From the perspective of resource utilization, RAC can consume a large amount of waste concrete masonry, reduce construction waste landfilling occupation, and replace natural aggregates to reduce mountain quarrying and river sand mining, realizing the protection of natural ecological resources. From the perspective of carbon emission reduction, the whole production process of RAC saves the mining, processing and transportation links of natural aggregates. Relevant life cycle assessment data show that the carbon footprint of RAC is 10%–30% lower than that of traditional concrete [19], which has significant low-carbon environmental benefits and can effectively help the construction industry achieve carbon peaking and carbon neutrality goals.

However, the large-scale popularization and industrial application of RAC still face many practical barriers. First, the quality stability is poor. The source of construction waste is complex and variable, and the strength, mortar content and impurity content of recycled aggregates from different demolition projects are different, resulting in inconsistent RAC performance, difficult unified quality control, and increased engineering design and construction risks. Second, the industry standard system is imperfect. At present, most countries lack unified RAC design specifications, testing standards and construction acceptance codes, resulting in irregular engineering application and difficult popularization

[20]. Third, the industry recognition and application awareness are insufficient. Most design units and construction enterprises still adhere to the traditional construction concept, lack practical RAC construction experience, and have concerns about the structural safety and durability of RAC projects, which restricts the market promotion of RAC.

In view of the above development obstacles, this paper puts forward targeted development suggestions: first, establish unified national and industrial technical standards for recycled aggregate concrete, formulate standardized aggregate grading, mix design, performance testing and construction acceptance specifications; second, increase investment in basic research and engineering demonstration research of RAC performance optimization, develop high-efficiency and low-cost aggregate modification technology; third, strengthen industry publicity and technical training, improve the professional ability of designers and constructors in RAC engineering application; fourth, introduce policy incentive measures, take green building certification, tax preference and subsidy policies to guide enterprises to actively apply RAC technology [21].

6. Conclusion

Recycled aggregate concrete, as a typical green and low-carbon building material, provides an effective solution for solving the problems of natural resource depletion, construction waste accumulation and high carbon emissions in the traditional construction industry, and has irreplaceable application value in sustainable civil engineering. Although recycled aggregates have inherent defects such as high water absorption, microcracks and residual mortar, which lead to the problems of reduced strength, poor durability and unstable performance of RAC, a variety of technical means including mix proportion optimization, aggregate physical and chemical modification, and advanced carbonation curing can effectively make up for the performance deficiencies of RAC and realize the stable improvement of comprehensive performance.

At present, RAC has achieved mature engineering applications in low and medium-rise building structural components, municipal road pavement bases, and various non-load-bearing precast components, verifying its engineering practicability and technical feasibility. With the continuous improvement of circular economy policies and green building systems, the standardization, industrialization and large-scale development of RAC have become an inevitable trend. In the future, with the improvement of unified industry standards, the breakthrough of high-efficiency performance optimization technology, and the support of policy incentives and industry popularization, recycled aggregate concrete will be widely used in more civil engineering fields, effectively promote the resource recycling of construction waste, reduce the carbon emission level of the construction industry, and lay a solid foundation for the comprehensive transformation and upgrading of civil engineering to green and sustainable development.

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