Research Status and Development Trends of Recycled Aggregate Concrete from Construction Solid Waste Blocks

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Abstract. With the acceleration of urbanization, the amount of solid waste generated from building demolition has increased significantly, with concrete accounting for 35% of the total. Driven by sustainable development strategies, the reuse of construction waste has become a research focus. Recycled concrete, produced by crushing, cleaning, and grading waste concrete blocks to partially or fully replace natural aggregates, exhibits performance comparable to ordinary concrete, along with excellent viscosity and impermeability. The addition of materials such as slag micropowder can further enhance its corrosion resistance and durability, making it suitable for harsh environmental engineering. Domestic and international studies indicate that the mechanical properties of recycled concrete are significantly influenced by the aggregate replacement rate, and the incorporation of fly ash or air-entraining agents can improve its workability and strength. Currently, the application of recycled concrete in infrastructure is expanding, and it is expected to play a greater role in high-performance concrete, complex environmental engineering, and ecological restoration in the future.

Keywords: Recycled aggregate concrete; Construction waste; Sustainable development; Mechanical properties; Ecological restoration.

1. Introduction

With the rapid development of urbanization, the amount of solid construction waste generated from the demolition of old buildings has gradually increased. As the construction industry advances, the production of construction waste continues to rise annually, with concrete accounting for 35% of the total. Under the gradual implementation of sustainable development strategies, technical departments have focused on the reuse of construction waste, integrating resources and combining mechanical equipment and technical processes to reprocess waste materials from construction. This achieves synergistic development between economic costs and environmental protection.

Recycled concrete refers to new concrete produced by crushing, cleaning, and grading waste concrete blocks, then mixing them in a certain proportion and gradation to partially or fully replace natural aggregates (mainly coarse aggregates), along with cement, water, and other components. Recycled aggregate concrete is particularly suitable for harsh environments, such as embankments and coastal defense projects. This not only saves transportation costs and reduces expenses but also benefits environmental protection, enhancing both economic and social benefits.

Currently, researchers worldwide have made significant progress in the recycling and reuse of concrete. Existing experimental results indicate that incorporating an appropriate amount of recycled concrete as coarse aggregate can achieve strength and durability comparable to ordinary concrete [1-3], and it has already been applied in practical construction projects. Compared to recycled concrete, research on the application of mixed recycled aggregates (recycled concrete + recycled bricks) in concrete is relatively limited [4]. However, the use of mixed recycled aggregates can reduce production costs, minimize environmental damage and pollution, and better meet the demands of construction projects [5].

2. Research Status of Recycled Aggregate Concrete from Construction Solid Waste Blocks

2.1 International Research Status

According to the global carbon dioxide emissions database, the construction industry ranks second in global carbon dioxide emissions [6], while consuming approximately 40% of energy. Among various building materials, the energy consumption and carbon emissions of cement and concrete are particularly significant, greatly impacting the environment and sustainability [7]. In one study, Tam [8] provided statistics on the recycling rates of total construction waste (municipal waste, construction waste, and other waste). Additionally, the survey found that Denmark, the Netherlands, Japan, and Germany far surpass other countries in construction waste recycling rates. According to statistics from the Environmental Protection Agency (EPA) [9], Hong Kong generated approximately 236×10^5 tons of municipal solid waste in 2015, with construction waste accounting for about 40.15%. Therefore, the recycling of construction waste and the use of green building materials are inevitable requirements for the sustainable development of the construction industry.

In the 1980s, the U.S. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as the Superfund Act, which explicitly prohibited the arbitrary dumping of industrial waste and mandated proper disposal. By the mid-1990s, nearly 100 highway paving projects in the U.S. had used recycled concrete from construction waste, and 15 states had issued relevant regulations [10]. Due to its lack of natural resources, Japan has placed particular emphasis on the resource recycling of construction waste. Japanese regulations explicitly require that design considerations include the efficiency of post-demolition recycling. To date, over 97% of Japan's construction waste has been recycled [11]. The massive destruction caused by World War II left Germany with large quantities of construction waste, making it the first country in the world to utilize construction waste on a large scale, primarily in highway construction projects [12]. By 2020, the recycling rate of construction waste in EU countries had reached 70%, 50% increase from a decade earlier [13].

2.2 Domestic Research Status

In contrast, China started late in the resource recycling of construction waste. Recycled concrete produced from construction waste remains in its preliminary stages and is mostly used in low-strength components such as road bases, with limited application scope. To promote the resource utilization of construction waste, systematic research on the mechanical properties of recycled concrete is essential to guide its engineering applications.

Zhang et al. (2015) found that the slump of recycled concrete decreases as the replacement rate of recycled coarse aggregate increases, with a more pronounced reduction at higher replacement rates [14]. This is because, under unchanged mix design conditions, the high water absorption of recycled aggregates absorbs part of the water intended for concrete mixing, reducing the effective mixing water and affecting slump. Liu et al. (2021) reached similar conclusions, showing that at the same water-cement ratio, slump gradually decreases with increasing recycled aggregate content [15]. Huang et al. (2017) noted that as the replacement rate of recycled coarse aggregate increases, the slump loss over time becomes more significant [16].

Wang et al. (2014) studied the relationship between the water absorption of recycled aggregates and the amount of attached mortar [17]. They found that as the amount of attached mortar increases, recycled aggregates absorb more water from the concrete mixture, reducing its fluidity. Many researchers have attempted to improve the workability of recycled concrete. Huang (2018) demonstrated that adding an appropriate amount of air-entraining agent can mitigate the low slump of recycled concrete and enhance slump retention [18]. The addition of air-entraining agents increases the air content in recycled concrete, with spherical bubbles acting as "ball bearings" to improve fluidity. Yuan et al. and Qiu et al. found that adding an appropriate amount of fly ash can increase concrete fluidity and improve workability. The spherical particles of fly ash act as ball bearings to enhance fluidity [19-20].

Gao et al. (2020) showed that when the replacement rate of recycled aggregates is 50% and 100%, the 28-day compressive strength of recycled concrete decreases by an average of 12.34% and 14.98%, respectively, compared to ordinary concrete [21]. Wang (2022) found that as the replacement rate of recycled aggregates increases, compressive strength gradually declines [22]. At a 50% replacement rate, the 28-day compressive strength decreases by 23.4%, and the 60-day compressive strength decreases by 13.8%. Regarding the change in strength loss rate of recycled concrete at different ages, Zhang et al. (2015) studied the strength loss rate of recycled concrete at four ages and found that the strength loss of recycled concrete with two replacement rates significantly decreased in later stages [23]. Similar to the studies by Gao & Wang (2020) and Wang (2022) [21-22], Kazmi et al. (2019) reported a compressive strength loss rate as low as 26% for recycled concrete prepared with 100% recycled aggregates [24]. Wang et al. (2021) discovered that not only does the replacement rate of recycled aggregates negatively affect the compressive strength of recycled concrete, but an increase in sand ratio is also a significant factor contributing to strength reduction [25]. In contrast, Lu (2021) found that strength initially increases and then decreases with the increase in recycled aggregate replacement rate, peaking at a 20% replacement rate [26].

Regarding the issue of high strength loss rates in recycled concrete, Wang et al. (2014) concluded from the fracture surfaces of concrete specimens during mechanical performance tests that the weakest point is the interfacial transition zone between old and new mortar in recycled coarse aggregate concrete [17]. Xiao et al. (2014) used digital image technology to digitize concrete interfaces, creating physical and finite element models of concrete cross-sections [27]. Through finite element simulation, they analyzed the stress-strain relationship and crack propagation process in concrete slices. They noted that initial cracks appear in the mortar and gradually connect with cracks in the aggregates, ultimately, penetrating cracks lead to specimen failure.

Many researchers have attempted to improve the mechanical properties of recycled concrete. Yuan et al. (2020) and Huang (2023) found that replacing cement with fly ash results in an initial increase followed by a decrease in compressive strength, with the optimal replacement rate being 10%–15% [19,28]. Fly ash reacts with $Ca(OH)_2$ in a secondary hydration process, producing calcium silicate hydrate (C-S-H) to enhance concrete strength. However, as the fly ash content increases, the $Ca(OH)_2$ generated by cement hydration decreases, leaving unreacted materials in the concrete that impair strength.

2.3 Research Level and Trends

Currently, China places significant emphasis on environmental protection and waste classification, making the resource utilization of construction waste imperative. In 2020, the market size for construction waste treatment in China reached 100 billion, and it is projected that by 2030, construction waste could generate an output value of 330 billion. The government has introduced numerous tax incentives and project funding rewards to encourage research institutions to continue advancing the study of solid waste resource utilization, achieve breakthroughs in key areas, and catch up with developed countries.

In recent years, bans and restrictions on the extraction of natural sand and marble have led to increasingly tight raw material supplies and rising prices, creating new opportunities for recycled sand and aggregate products derived from construction waste. The rational application of big data can quickly determine the stock and production of urban construction waste, match market demand, accurately identify product types, and achieve precision production. At present, the upstream, midstream, and downstream industrial chains in China are not yet fully developed. Research on construction waste recycling technology started relatively late, but the resource utilization industry for construction waste is now in a phase of rapid development. Enterprises engaged in construction waste resource utilization require Build-Operate-Transfer (BOT) to allocate and utilize the residual value of construction waste, transferring it into recycled building materials and establishing a complete industrial chain — collection, processing, and reuse — to maximize resource value transfer. Policy changes, technological updates, industrial chain extension andintersection, and the integration of big data can all effectively promote macro-level enterprise planning.

For recycled aggregate concrete from construction waste to achieve comprehensive application in infrastructure projects, extensive applied research will form new trends in multiple areas.

First, ultra-high-performance concrete (UHPC) is one of the high-value utilization directions for construction waste. When recycled aggregates are incorporated into UHPC, they are typically used in the form of recycled micropowder as a supplementary cementitious material to replace cement. Due to the high water absorption of recycled micropowder, the fluidity of UHPC decreases as the replacement rate increases. Peng et al. (2019) demonstrated that when the replacement rate of recycled micropowder reaches 50%, the fluidity declines by 42.9% [29]. The study also noted that the incorporation of recycled micropowder reduces the mechanical performance of UHPC. At replacement rates of 30% and 50%, the 28-day compressive strength decreases by 15.4% and 30.3%, respectively, while the flexural strength decreases by 1.1% and 12.1%. Jiang et al. (2020) found that as the replacement rate of recycled micropowder increases from 0% to 45%, the compressive and flexural strengths decrease by 12.9% and 13.2%, respectively [30]. However, Peng et al. (2019) reported that UHPC with recycled micropowder still exhibits excellent impermeability [29]. When subjected to the maximum water pressure (4.0 MPa), no water penetration was observed in the specimens, indicating that the impermeability grade of the UHPC matrix exceeds P39.

Currently, only a few studies have applied recycled aggregates to UHPC, and further research is needed to determine its feasibility. According to Zhou (2023) recycled aggregates can be used in dry-mix recycled mortar and recycled wall panels, which have high market demand, profitability (20%~25%), and recycled aggregate content, making them suitable products for construction waste recycling [31]. Recycled aggregates can also be incorporated into non-fired bricks, which, despite lower profit margins, have substantial market demand and are currently the dominant products for construction waste recycling. The application fields of large-block recycled aggregate concrete from construction waste will continue to expand. Beyond traditional uses in buildings and road surfaces, it may also be applied to more demanding environments such ashydraulic engineering, marine engineering, and underground engineering, necessitating in-depth research on its performance under varying conditions.

Additionally, recycled aggregates from construction waste blocks are typically porous materials coated with mortar, exhibiting higher water absorption and lower density compared to natural aggregates. As a result, permeable or vegetation-compatible concrete using recycled aggregates will be a key research focus in the coming period. The porous nature of permeable concrete ensures the stability of embankment slopes while supporting vegetation growth and controlling rainwater infiltration, thereby protecting and improving the natural ecological environment of riverways [32]. It is an innovative material that cannot be overlooked in embankment engineering.

The above analysis demonstrates that the theoretical and mechanical properties of recycled aggregate concrete from construction waste blocks are well-established. Although it has been widely applied in civil engineering and highway engineering, further research is still required in areas such as high-performance concrete, engineering applications in complex environments, and the preparation and construction processes of recycled concrete.

For ecological restoration and stability protection of riverbanks, reservoirs, and channel banks, this study leverages the low density and permeability of recycled aggregate concrete to develop permeable or vegetation-compatible concrete using construction waste blocks as recycled aggregate concrete. This material can be applied to ecological restoration and slope protection projects, overcoming the limitations of traditional vegetation-based ecological restoration and engineering protection techniques.

3. Summary

Recycled aggregate concrete demonstrates significant potential in the resource utilization of construction waste, with performance optimization and application expansion being key focuses for future research. By improving aggregate processing techniques and additive formulations, its mechanical properties and environmental adaptability can be further enhanced. Additionally, policy support and technological innovation will promote the widespread application of recycled concrete in high-performance materials and ecological engineering, providing critical support for the sustainable development of the construction industry.

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