

Analysis on Performance and Carbon Emission of Recycled Aggregate Concrete

Ye Tao *

Department of Swjtu-Leeds Joint School, Southwest Jiaotong University, Chengdu, China

* Corresponding Author Email: lele@my.swjtu.edu.cn

Abstract. Climate change is a major global challenge, of which carbon dioxide is a particularly significant contribution. The construction industry has a significant impact on carbon emissions, especially the concrete production process, which not only consumes a lot of energy, but also produces a lot of carbon dioxide along with carbonate decomposition. Therefore, the properties and carbon emission analysis of recycled aggregate (RCA) concrete are discussed in this paper. Firstly, the preparation technology of RCA concrete is discussed. Then the factors affecting the performance of concrete and the modification methods of RCA are analyzed to improve the performance of concrete. Finally, the carbon emission of RCA concrete in the raw material production stage is compared with that of conventional concrete. The results show that RCA concrete has only 84.1% of the carbon emissions of conventional concrete, which is a very effective measure to reduce emissions in the construction industry. This paper aims to provide theoretical support for tackling climate warming and reducing carbon emissions in the construction industry by studying the preparation, performance and carbon emissions of RCA concrete materials.

Keywords: Carbon emission, recycled aggregate concrete, concrete modification.

1. Introduction

In recent years, global warming has caused serious damage to the ecological environment. With the development of the construction industry, the carbon emission of construction projects has a non-negligible impact on the environment. According to the research report on China's Building Energy Consumption and Carbon Emission (2023), from 2017 to 2021, the carbon emission CO₂ in the whole process of building construction in China reached 4.07 billion tons [1].

Concrete is widely used in the construction industry, and its whole process from raw material mining to production, transportation, use and even waste will produce a large amount of carbon emissions. Studies have shown that the carbon footprint of concrete contributes 20%-50% to global warming in the materialization stage, while the carbon footprint of building use and maintenance stage accounts for 34%-70% of the carbon footprint of its entire life cycle [2]. According to the Carbon Emission Report of China's Building Materials Industry (2020) released by China Building Materials Federation, the CO₂ emission of cement industry is 1.23 billion t, accounting for 16% of China's carbon emission [3]. All these problems reveal the grim situation of ordinary concrete in terms of carbon emissions.

The International Energy Agency (IEA) has also clearly proposed a plan to capture 27.4 million tons of cement-generated CO₂ per year from 2030 [4]. Compared with ordinary Portland concrete, green concrete can reduce carbon emissions by 3.5%-25.7%, which is a very good choice [5]. In addition, carbon emissions can be further reduced by optimizing the mix ratio, using recycled aggregate (RCA) to prepare concrete or iron tail-sand green concrete.

This paper mainly studies the preparation, properties and application of two kinds of green concrete, RCA concrete and iron tail sand green concrete. The difference in carbon emission between the new concrete technology and the traditional concrete is analyzed, so that the importance and necessity of green concrete can be explained more clearly. The results of this study make clear the advantages of green concrete, which allows for more informed choices based on the specific environment in practical applications.

2. RCA Concrete

2.1. Raw Materials and Modification Processes

RCA is the main raw material for the preparation of RCA concrete, which comes from a wide range of sources, including discarded concrete, bricks, blocks and other construction wastes. About 50 tons of usable construction waste, such as concrete piles, were generated during the construction of the "ice ribbon" for the Beijing Winter Olympics. In order to realize the reuse of construction waste, Beijing Urban Construction Group cooperated with Beijing Shougang Resources Comprehensive Utilization Technology Development Co., Ltd. to process these construction waste into RCA. Through reasonable mix design, they successfully produced C45 RCA concrete, which was used to produce concrete stand components [6]. This process not only effectively recovers the waste, but also provides a practical basis for the preparation of RCA concrete. The preparation process of RCA concrete is shown in Fig. 1.

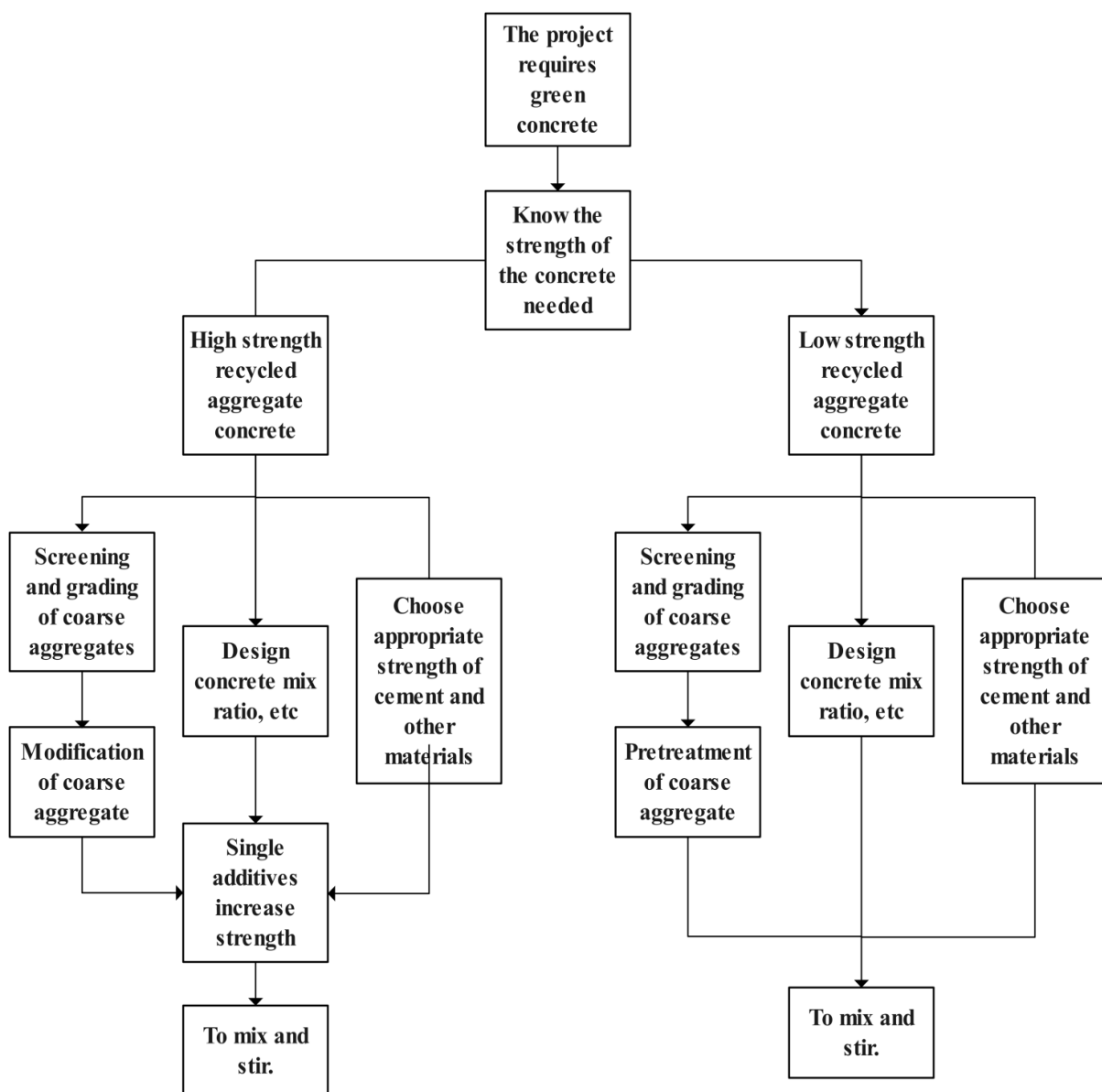


Fig 1. Preparation process of RCA concrete.
 (Picture credit: Original)

2.2. Factors Influencing Performance

Research shows that the compressive strength, elastic modulus and other mechanical properties of RCA concrete are affected by the quality of RCA, replacement rate, water-cement ratio and other characteristics [7]. With the increase of the replacement rate of regenerated aggregate, the compressive strength of regenerated concrete increases first and then decreases. When the replacement rate of RCA is between 12% and 24%, the 28-day compressive strength of recycled concrete can reach about 42 MPa, showing good compressive performance [8].

In addition, the shape of the coarse aggregate also has a significant effect on the performance of concrete, and the recycled coarse aggregate with suitable characteristics is used to replace the natural primary aggregate. Aggregates with high surface roughness will have higher yield strength and plastic viscosity, while aggregates with fewer edges and higher sphericity will have higher fluidity and lower rheological parameters [9]. Therefore, grading the aggregate is a very important step.

RCAs collected from construction waste are of unknown origin and vary in properties. Therefore, both high strength and low strength recycled concrete need to be screened and graded. The main purpose is to divide RCA into different grades according to particle size and different strengths according to strength [10].

For concrete with low aggregate strength requirements, only RCA pretreatment of RCA is required to reduce its water absorption and improve its adhesion with cement slurry. Common pretreatment methods include saturated surface dry method [11]. The mix design of RCA concrete is one of the key factors affecting its performance. Table 1 is an excellent case for C30 RCA concrete.

Table 1. C30 RCA mix (Data from: [12]).

Material name or property	Material proportion or value	
The ratio of material	Coarse and fine RFA	55%
	Recycled powder	10%
	Cement	20%
	Fly ash	10%
	Mineral powder	5%
	Ratio of water to material (A)	11.50%
RFA particle size distribution	plasticizer (B)	0.90%
	2.5~5.0 mm (α)	50%
	0.5~2.5 mm (β)	50%
Physical property	Thermal conductivity	0.4636 W/m·K
	Intensity	25.8 MPa

2.3. Modification of RCAs

There are old mortar and fine cracks attached to the surface of RCA, so the RCA has the problems of high-water absorption and high crushing index [13]. For concrete with high strength demand, simple pretreatment is not enough to meet the demand of performance. Therefore, recycled concrete with RCA as raw material usually has poor performance. If the strength of RAC concrete needs to be further improved, the performance needs to be modified with RCA. At present, the common modification methods are shown in Table 2. The modification improves the apparent density and bulk density of coarse aggregate, and makes its performance close to that of traditional aggregate [14].

Table 2. Modification method of RCA (Data from: [15]).

Method of modification	Principle	Main effect	
Acidification modification method	Use HCl, H ₂ SO ₄ , CH ₃ COOH, H ₃ PO ₄ and other acid solutions to treat RCA, so that the alkaline substances adhering to the surface react with the acid, weaken the adhesion of the old mortar and dissolve it	The microstructure of RCA was improved and the water absorption rate was reduced	
Polymer emulsion modification method	RCA was treated with polymer emulsions such as polyvinyl alcohol (PVA) to repair micropores and cracks	The RCA strength is increased and the porosity and water absorption are reduced	
Chemical slurry modification method	Cement slurry modification method	The cement slurry is soaked or wrapped in RCA, and the cement slurry reacts with the active ingredients in RCA to generate new hydration products	Fill cracks and pores to improve microstructure
	Volcanic ash slurry modification method	Add mineral admixture such as fly ash and silica fume into cement slurry to make active slurry and soak RCA	Optimize microstructure and enhance performance
	Sodium silicate solution modification method	Hydrated calcium silicate and silicate gel were generated by the reaction of Ca(OH) ₂ with sodium silicate solution	Repair cracks, strengthen old mortar, improve strength and compactness
Modification by nanotechnology	The volume effect of nano-SiO ₂ or other nano-materials and the reaction with Ca(OH) ₂ in RCA were used to generate hydrated calcium silicate gel	Improve microstructure, improve performance	
Carbonization modification method	Silica gel and CaCO ₃ crystal were formed by the reaction of CO ₂ with hydrated calcium silicate and Ca(OH) ₂ in RCA surface adhesive mortar	Repair cracks and micropores, compact structure, improve performance	
Microbial mineralization modification method	The CO ₂ generated by microbial metabolism reacts with Ca ²⁺ to generate CaCO ₃ , which forms crystals and penetrates into the RCA interior to repair and fill pores and cracks	Improving RCA performance	
Composite technology modification method	Two or more modification methods were combined to improve the RCA performance in a targeted manner	The advantages of various modification methods were integrated to meet the expected application requirements	

3. Comparison of Carbon Emission between Green Concrete and Traditional Concrete

According to the study of the United Nations Environment Programme (UNEP), the construction sector accounts for 21% of global greenhouse gas emissions [16]. As the core material of modern architecture, concrete is widely used in various engineering construction, and it emits a large amount of CO₂. The carbon emission of traditional concrete is mainly concentrated in the production process of cement, accounting for 77.53%- 91.75% of the whole life cycle [17]. This paper focuses on the carbon emissions in the manufacturing process and analyze the differences between traditional concrete and green concrete in terms of carbon emissions. According to the calculation standard of building carbon emission: GB/T 51366-2019, the total carbon emission calculation formula of the whole life cycle of concrete is calculated as Eq. (1) [18]. In this paper, the production part C₁ is mainly calculated.

$$C = C_1 + C_2 + C_3 + C_4 \quad (1)$$

Where C_1 is the carbon emission generated by raw material production (kg), C_2 is the carbon emission when transport to production equipment (kg), C_3 is the carbon emission during concrete mixing (kg), and C_4 is the carbon emission when transported to the construction site (kg).

3.1. Carbon Emissions of Conventional Concrete

3.1.1. Carbon missions from raw material production

In this paper, C30 concrete is used as an example to calculate carbon emissions. The influence of additives on the carbon emissions of conventional and RCA concrete is very small, so it is not calculated here. The carbon emission generated by raw material production C_1 is calculated by Eq. (2). Table 3 shows the quality of raw materials required per cubic C30 concrete.

$$C_1 = \sum_{i=1}^n Q_i R_i \quad (2)$$

Where Q_i is the quality of i raw materials produced (kg), R_i is the carbon emission factor of 'i' raw materials (kgCO₂e/kg).

Table 3. Mass of raw material required per cubic C30 concrete (Data from: [19]).

Raw materials	Water	Cement (P.O42.5)	Mineral powder (S95)	Fly ash (C-II)	Sand (Machine-made)	Stone (5-25mm)
Mass (kg)	170	200	67	67	840	986

According to the relevant specifications GB/T 51366-2019 "Building Carbon Emission Calculation Standard" and T/CBMF 27-2018 "Ready Mixed Concrete Low Carbon Product Evaluation Methods and Requirements", Table 4 is the carbon emission factor of the required materials [19, 20].

Table 4. Carbon emission factor of required materials (Data from: [19, 20]).

Raw materials	Water	Cement (P.O42.5)	Mineral powder (S95)	Fly ash (C-II)	Sand (Machine-made)	Stone (5-25mm)
Carbon emission factor (kgCO ₂ e/kg)	0.000168	0.735	0.0624	0.0345	0.0417	0.00218

According to the data summarized in the specification, the carbon emission generated by the production of traditional concrete raw materials is calculated as 190.5 kgCO₂ by substituting it into Eq. (2).

3.2. Carbon Emissions of RCA Concrete

The amount of water, P.O42.5 cement, S95 mineral powder and C-class fly ash are the same, and no additional calculation is needed. When the replacement rate of recycled coarse aggregate is 100%, it is mainly obtained by crushing and other operations in the production process, and there is no hidden carbon emission of the material in the production part. However, due to the large amount of energy required for dismantling and crushing or strengthening aggregate processing, the carbon emission of this part needs to be calculated by the carbon emission caused by the use of fossil fuels and electricity.

$$C_{\text{energy}} = \sum_{i=1}^n E_i K_i \quad (3)$$

Where E_i is the amount of the 'i' energy source, K_i is the carbon emission factor of the energy in 'i' item. Table 5 shows the carbon emission factors of different energy types listed according to DB11/T1959-2022 "Energy Consumption Limit of Prefabricated Building Components" [21].

Table 5. Carbon emission factors of different energy types (Data from: [21]).

Type of energy	Carbon emission factor
Electric energy	1.246 kgCO ₂ /kW·h/kg
Diesel oil	3099.56 kgCO ₂ /t
Natural gas	2.16 kgCO ₂ /m

The power consumption of producing 1t RCA is 1.906kW·h, and the diesel consumption is 0.42 kg [22]. According to the normative data, energy emission 6.7 kgCO₂ can be obtained by substituting into Eq. (3), so carbon emission of RCA concrete is 160.2 kgCO₂.

3.3. Discussion

In this paper, compared the carbon emissions of the two kinds of concrete, the carbon emission of RCA concrete is 84.1% of that of traditional concrete, indicating that its production process is more energy saving and environmental protection. According to the research results of Wei et al., RCA concrete with different reinforced aggregate types can reduce carbon emissions by about 10%-20% [11]. It is consistent with the 15.9% calculated in this paper. Since this paper only calculates the carbon emissions in the process of raw material production, the 15.9% in this paper is slightly larger than the carbon emissions in the whole life cycle.

RCA concrete has significant carbon emission reduction benefits and can be used as a green building material in low-carbon buildings. The advantages of carbon emissions for the construction industry to reduce energy consumption and greenhouse gas emissions will also promote the development of circular economy, reduce the overall burden of the construction industry on the environment, and contribute to the realization of sustainable urban development.

4. Conclusion

In this paper, the preparation process and performance factors of RCA concrete are mainly studied, and the carbon emissions of traditional concrete and RCA concrete are compared and analyzed, and the following conclusions are drawn:

(1) Through the study of the preparation process of RCA concrete and the main influencing factors of its performance, it is found that the focus is on the production of RCA and the design of coordination. In addition, acidification, chemical slurry nanotechnology and other technologies can be used to modify the RCA, so as to improve the performance of RCA concrete.

(2) Through the calculation and comparative analysis of the carbon emission of raw materials production of traditional concrete and RCA concrete, the results show that the emission of traditional concrete is about, and that of RCA concrete is about. Compared with traditional concrete, RCA concrete can effectively reduce carbon emissions, about 84.1% of the traditional. The production and use of RCA concrete is a very effective measure to reduce carbon emissions in the construction industry.

(3) RCA concrete still has the problems of unstable quality, lack of durability and friction, which limits its wide application. In the future, its further development in green buildings can be promoted by optimizing aggregate handling technology, improving the comprehensive performance of concrete and some support from government policies.

Reference

- [1] Research report on energy consumption and carbon emission of buildings in China (2023). Architecture, 2024, (02): 46-59.
- [2] Li Hui, Deng Quanxue, Zhang Jingxiao. Research on environmental emission and material carbon footprint of reinforced concrete construction oriented to building types. Ecological Economics, 2019, 35(03): 194-200.

- [3] China building materials industry carbon emissions report (2020). *Journal of building materials in China*, 2021, (4): 59-62.
- [4] CCUS Projects Explorer-Data Tools, IEA. <https://www.iea.org/data-and-statistics/data-tools/ccus-projects-explorer>.
- [5] Xiao Yu, Wu Shuigen, Xiao Jianzhuang, et al. Carbon emission analysis of green concrete. *Building Construction*, 2019, 41(02): 312-317.
- [6] Yuan L. Concrete in "ice ribbon" creates a Chinese miracle, looking forward to "together to the future". *World of Concrete*, 2022, (02): 13-17.
- [7] Xiao Jianzhuang, Tang Yuxiang, Zhang Kaijian, et al. Stress - strain relationship of recycled coarse aggregate concrete. *Engineering Mechanics*, 2024, 41(02): 43-55.
- [8] Zou Yan, Cao Dafu. Study on the application of recycled aggregate in concrete. *New building materials*, 2020, 47(4): 3331-3338.
- [9] Ge Zhi, GAO Tianming, Wang Siqu, et al. Effect of coarse aggregate characteristics on flow performance of freshly mixed self-compacting concrete. *Concrete*, 2024, (07): 169-173.
- [10] Tang Lei, Li Leilei, Xin Jianghui. Research on processing technology of recycled construction waste aggregate. *Brick and Tile*, 2024, (11): 34-37.
- [11] Wei Maozhi, Lin Mingqiang, Xie Qun, et al. Study on life-cycle carbon emission analysis and calculation method (model) of recycled aggregate concrete. *Concrete*, 2024, (7): 1-8.
- [12] Su Xiaowei, Wang Anqi, Xiao Junrong, Yang Zhenhuai, Fu Yibing, Wu Xutao. Experimental study on preparation and compressive strength of recycled aggregate concrete. *Journal of Anhui Vocational and Technical College of Water Resources and Hydropower*, 2021, 21(3): 8-12.
- [13] Geng Mingyang, Li Xiaohua, Zeng Zhi, et al. Study on preparation and performance test of fully recycled fine aggregate concrete. *Journal of Hunan Institute of Engineering (Natural Science Edition)*, 2024, 34(01): 68-75.
- [14] Sun Fei, Du Jiabao, GAO Qiang, et al. Study on macro and micro characterization and physical and chemical characteristics of construction waste recycled aggregate. *Sichuan Cement*, 2021, (02): 17-19.
- [15] Wei Hongjun, Yan Hongsheng, Zhu Yaguang, et al. Study on modification of properties of recycled coarse aggregate by chemical strengthening. *Journal of Shandong Agricultural University (Natural Science Edition)*, 2021, 52(06): 1009-1016.
- [16] Li Keqing, Qi Guoqiang, Cao Fangfei, et al. Research progress on characteristics and modification methods of recycled aggregates from construction waste. *Concrete and Cement Products*, 2024, (11): 115-120.
- [17] 2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector. 2024.
- [18] Song H Y. Study on carbon emission calculation and carbon emission reduction path of ready mixed concrete. *Building Construction*, 2024, 46(09): 1432-1436.
- [19] GB/T 51366-2019, Building Carbon Emission Calculation Standard, 2019.
- [20] T/CBMF 27-2018, Evaluation Methods and Requirements for Low Carbon Products of Ready Mixed Concrete, 2018.
- [21] DB11/T1959-2022, Energy Consumption Limit of Prefabricated Components in Prefabricated Buildings, 2022.
- [22] Wu Shuan, Jiang Yehao, Wang Xin, Wang Bing. Calculation of carbon emission in life cycle of recycled concrete pavement brick. *Construction Technology*, 2014, 43(24): 32-36.