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SUSTAINABLE DESIGN OF RECYCLED CONCRETE USING SHAPE OPTIMIZATION AND CARBON DIOXIDE EMISSION BASED ON LCA

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Abstract. Switching from waste concrete disposal to recycling is urgently needed to enhance resource efficiency and reduce carbon emissions. This paper proposes a sustainable design framework for recycled concrete, incorporating shape optimization and carbon dioxide (CO_2) emission analysis using life cycle assessment (LCA). Using recycled concrete in infrastructure projects, this paper develops a carbon dioxide emissions accounting model based on LCA. Two water-cement ratios (WCR) and four recycled concrete aggregate replacement rates (RCARR) were tested on two natural aggregate concrete (NAC) and six recycled aggregate concrete (RAC) samples. Furthermore, four shapes options for the RAC structural member were designed, optimized, and compared. The G35 Expressway slope projects were used as a case study. The results showed that the regular hexagonal RAC structural member was selected for the project, achieving a carbon reduction rate of about 9%. The study also found that 1) life cycle carbon emission decreases with the increase of WCR and RCARR, respectively; 2) compared to NAC, the key processes of carbon emission reduction of RAC include the raw material acquisition and transportation stage as well as the carbonization absorption stage; 3) there is a transport distance threshold, beyond which the life cycle CO_2 emissions of RAC exceed those of NAC.

Keywords: recycled concrete, carbon dioxide emissions, shape design optimization, infrastructure.

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1. Introduction

The construction industry consumes significant natural resources and contributes substantially to global greenhouse gas emissions. Additionally, it generates large amounts of construction waste, much of which ends up in landfills, leading to environmental degradation (Zhu et al., 2020, 2023; Xu et al., 2024). Concrete is one of the most widely used building materials and a major contributor to carbon emissions. It is estimated that the cement production from China is responsible for roughly 5% of global greenhouse gas emissions, which is the main component of concrete. Additionally, China produces 1.6 billion tons of construction waste annually, with waste concrete comprising the majority (Xiao et al., 2021; Y. Gao & M. Gao, 2024). Worse still, waste concrete is often transported to rural areas or city outskirts for landfill or open storage without treatment, causing environmental pollution (Cheng et al., 2022; Wang et al., 2024). In response to natural resource scarcity and global warming concerns, the Chinese government has imposed strict restrictions on the mining of river sand and gravel, commonly used as fine and coarse aggregates in concrete. Therefore, an urgent shift from waste concrete landfill to recycling is needed to improve resource efficiency and reduce carbon emissions. This has gained considerable attention from both academics and practitioners (Besklubova et al., 2023).

In general, waste concrete can be recycled into bricks, road base fillings, and prefabricated concrete components. Specifically, depending on the mix design, RAC can be used in buildings (Kursula et al., 2024; Zhang, 2020; Tošić et al., 2019; Guo et al., 2018) and infrastructures (Xia et al., 2024; Li, 2019; Poon & Chan, 2007), as shown in Figure 1. However, the service life of concrete in buildings and infrastructure is relatively short (approximately 20–30 years). Most demolished concrete exhibits only minor breakage and cracks, yet frequent construction, demolition, and transportation activities consume large amounts

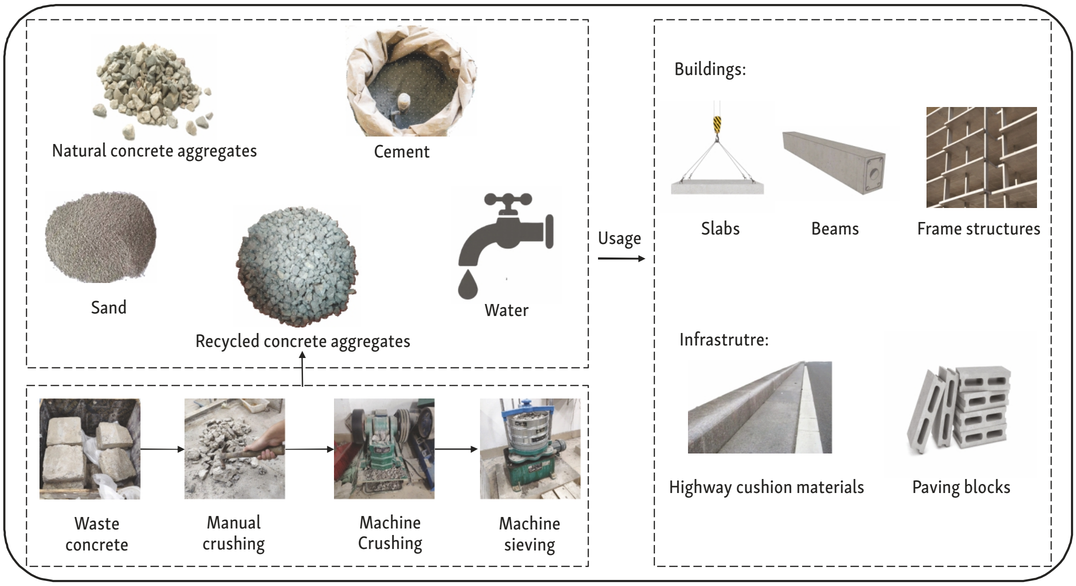

Figure 1. RAC composition and usage

of energy and produce substantial CO_2 emissions. In infrastructure projects (e.g., roads and bridges), waste concrete typically has higher strength and cleanliness than that from buildings (Zhou et al., 2024), and it is also more traceable (Cheng et al., 2021). Therefore, recycling waste concrete in infrastructure is particularly important.

Previous studies have examined the mechanical properties and durability of RAC, showing that it can perform similarly to NAC (Huda et al., 2020; Junaid et al., 2022). In the context of China's goals for carbon peaking by 2030 and carbon neutrality by 2060, along with rapid urbanization, recycling waste concrete in infrastructure is an effective and promising strategy to reduce CO_2 emissions. However, few studies have explored the sustainable design of RAC applications, considering shape optimization based on infrastructure project characteristics and life cycle carbon emissions. The main contributions of this study are twofold. First, this paper develops a carbon dioxide emissions accounting model for concrete using the LCA method and designs various shapes of recycled concrete structural members based on project characteristics. Second, a sustainable design for RAC applications, considering material mix proportions, shape optimization, and CO_2 emission reduction, is developed and analyzed to expand strategies for reducing carbon emissions.

2. Literature review

As constraints on construction waste increase, RAC has garnered significant attention from scholars (Lei et al., 2022; Zhao et al., 2023; Huang & Jian, 2023; Marinho et al., 2022). Many studies have measured the CO_2 emissions of RAC using the life cycle assessment (LCA) method (Liu et al., 2024; Malindu et al., 2022), but limitations remain in existing research. First, the carbon accounting boundaries for both NAC and RAC remain controversial. Most studies focus on CO_2 emissions from specific life cycle phases (e.g., material production, transportation, or construction). For example, Marinković et al. (2010) measured RAC CO_2 emissions during raw material extraction and production stages in reinforced concrete building structures. Results showed that the total CO_2 emissions difference between NAC and RAC depends on the transport distance and type of natural and recycled aggregates. Mroueh et al. (2001), Sereewatthanawut and Prasittisopin (2020) and Butera et al. (2015) assessed the environmental impacts of RAC for pavement structures and road sub-bases, finding that its impact was less than direct landfilling. Second, few environmental standards or comparative assessments exist for RAC applications in infrastructure. Existing CO_2 emission standards for RAC primarily focus on buildings. For instance, LEED in the United States and China's Standard for Building Carbon Emission Calculation (GB/T 51366-2019) (Ministry of Housing and Urban-Rural Development, 2019). Similarly, previous comparative studies on recycled concrete carbon emissions focus on buildings (Li et al., 2011). For example, Xiao and Lei (2008) and Xiao et al. (2021) constructed a life cycle carbon emission accounting model for concrete, using NAC and RAC buildings as comparative examples. However, unified carbon emission estimation models or standards for RAC in infrastructure have not yet been established.

The above literature provides a foundation for CO_2 emission assessments of RAC applications. However, specific assessments, comparisons, and optimizations for RAC in infrastructure are rarely addressed. To fill this research gap, this paper focuses on Expressway slope projects and develops a CO_2 emissions estimation model for concrete based on the LCA method. Variables such as WCR, RCARR, and transportation distance are chosen as key factors to explore their effects on RAC CO_2 emission reduction. Different shape designs of RAC paving bricks for slope projects were assessed, compared, and optimized for CO_2

emission reduction and stability. The results may serve as a reference for carbon emission reduction in other infrastructure and construction models.

3. Methodology

The methodology of the paper is shown in Figure 2.

3.1. Carbon emissions assessment based on the LCA

3.1.1. Research scope

The life cycle CO_2 emission boundary in this study encompasses raw material extraction and processing, transportation of raw materials, manufacturing of natural and recycled concretes, transportation to the construction site, construction, carbonization absorption, and demolition (as shown in Figure 3).

3.1.2. Functional unit

In this study, 1 m^3 of NAC and RAC is chosen as the functional unit (FU) to ensure a fair comparison of strength and durability. Both RAC and NAC exhibit similar basic mechanical properties (>C30) and meet the functional requirements of slope projects in the studied region. Additionally, NAC and RAC show similar durability as they are used in a non-aggressive environment.

In this study, NAC is designed with two water-cement ratios (WCR), and RAC with two WCR and three recycled coarse aggregate replacement rates (RCARR) of 30%, 50%, and 100%, resulting in eight types of concrete samples. The preparation of the eight concrete types follows the mix proportions in Table 1. All strength values are based on 28-day experimental results from this study. The water is sourced from local tap water, cement used is P.O 52.5R, natural aggregates and sand are obtained from a remote area in the region, and recycled concrete aggregates (RCA) are derived from waste concrete with an original strength grade of 40. Natural coarse aggregate is made of continuously graded artificial gravel with a particle size of 5~20 mm, of which 5~10 mm gravel accounts for 60% and 10~20 mm gravel accounts for 40%. According to the requirements of Reclaimed Coarse Aggregate for Concrete (GB/T 25177-2010) (Administration of Quality Supervision, Inspection and Quarantine of People's Republic of China & Standardization Administration of China, 2010) the reclaimed coarse aggregate is manually broken, cleaned and graded into coarse aggregate with a particle size of 5~20 mm. In addition, the macroscopic composition of recycled aggregates includes the stone wrapped partly cement mortar, a small part of the stone completely separated from the mortar and wrapped cement mortar.

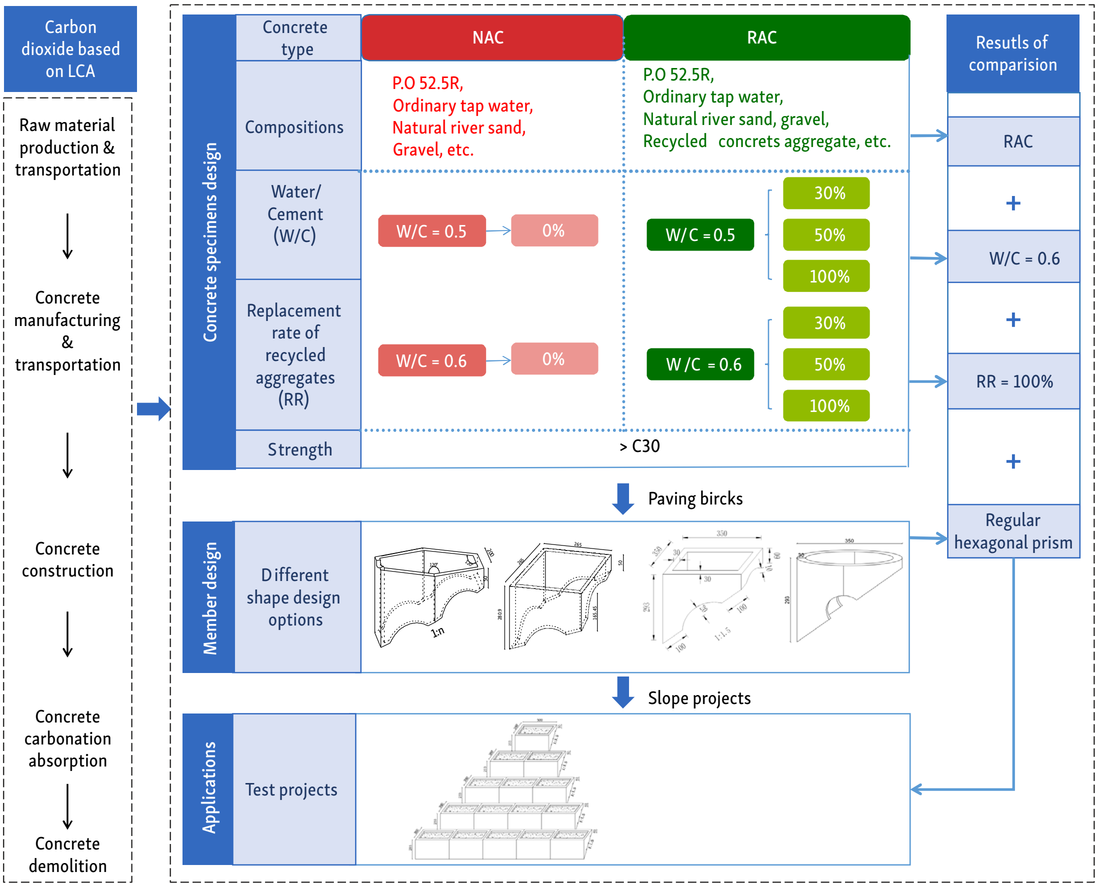

Figure 2. Schematic diagram of the research methodology

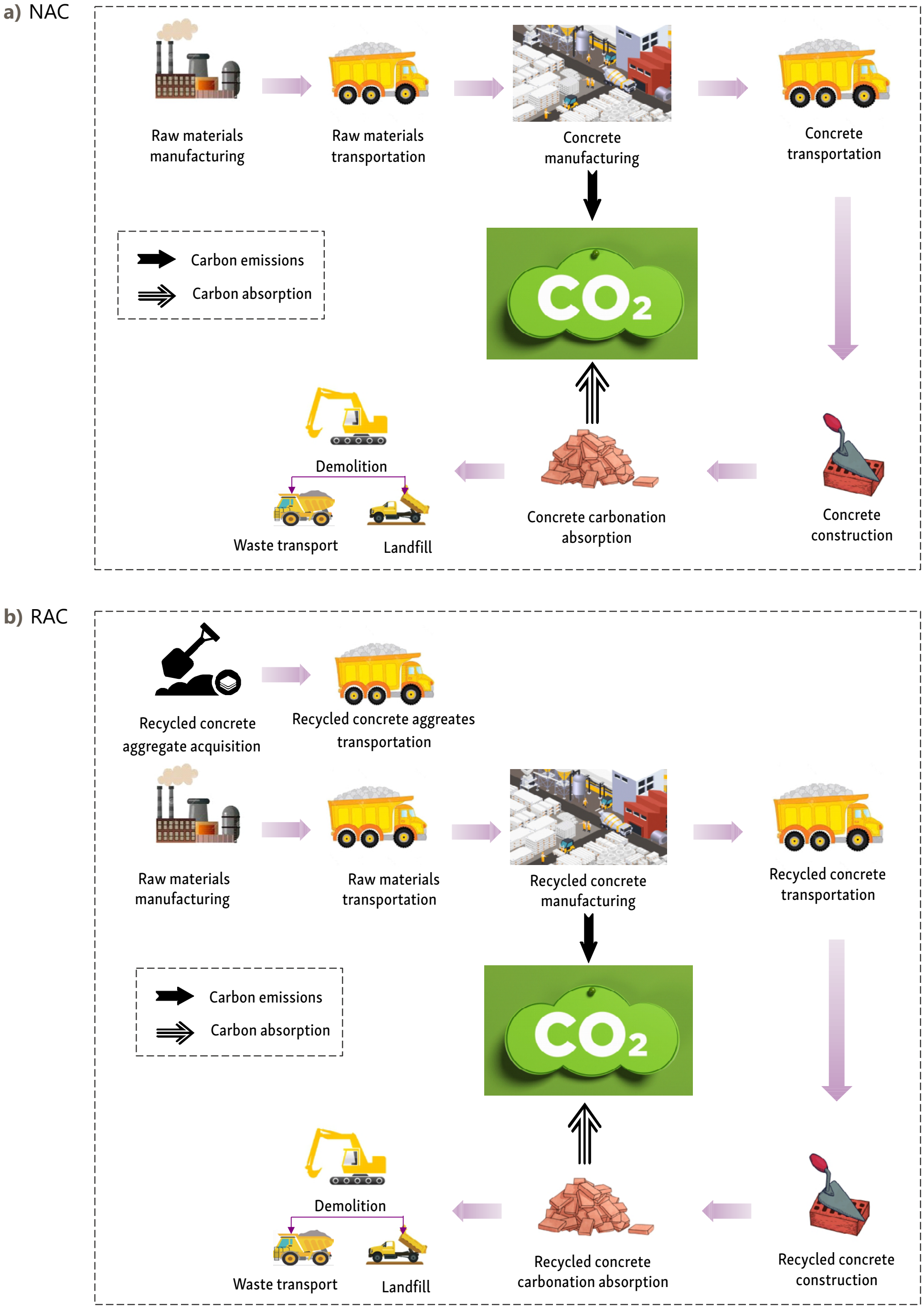

Figure 3. Boundary of life cycle CO_2 emission calculation of concrete

Table 1. Mix proportions of 1 m^3 of NAC and RAC

Types	WCR	RCARR	Water (kg)	P.O 52.5R (kg)	NA (kg)	RCA(C40) (kg)	Sand (kg)	Strength (MPa)
NAC^a	0.5	0	195	390	1179.75	0	635.25	51.96
RAC-30^a	0.5	30	195	390	825.825	353.925	635.25	45.01
RAC-50^a	0.5	50	195	390	589.875	589.875	635.25	36.04
RAC-100^a	0.5	100	195	390	0	1179.75	635.25	48.28
NAC^b	0.6	0	195	325	1222	0	658	51.50
RAC-30^b	0.6	30	195	325	855.4	366.6	658	38.17
RAC-50^b	0.6	50	195	325	611	611	658	37.06
RAC-100^b	0.6	100	195	325	0	1222	658	49.36

Notes: "a" and "b" in the NAC^a and NAC^b refer to W/C = 0.5 and W/C = 0.6, respectively.

3.1.3. Model construction

(1) Raw material production and transportation phase

The CO_2 emissions (C1) consist of two parts:

1) CO_2 emissions from the production of raw materials (C1a) include the CO_2 emissions from the processing of the raw materials, the corresponding calculation formula is shown in Eqn (1):

$$C1a = \Sigma M_i \times EF_i, \tag{1}$$

where C1a refers to the CO_2 emissions from the production of raw materials, $kgCO_2e$; M_i is the mass of material i required for 1 m^3 NAC or RAC, kg; EF_i is the CO_2 emission factor for the raw material i, $kgCO_2/kg$.

2) CO_2 emissions from the transport of raw materials to the manufacturing plant (C1b), the corresponding calculation formula is shown in Eqn (2):

$$C1b = \Sigma M_i \times D_i \times ET_i, \tag{2}$$

where C1b refers to the CO_2 emissions from transportation to the manufacturing plant, $kgCO_2e$; D_i is the transport distance of material i, km; ET_i is the CO_2 emission factor per unit mass transport distance for material i, $kgCO_2/(kg \cdot km)$.

(2) NAC and RAC manufacturing phase

CO_2 emissions from the manufacturing process of concrete (C2) are mainly the energy consumption of machine and equipment, the corresponding calculation formula is shown in Eqn (3):

$$C2 = \Sigma e_j \times K_j, \tag{3}$$

where C2 refers to CO_2 emissions from concrete manufacturing, $kgCO_2e$; e_j is the energy consumption of category j in the production of 1 m^3 concrete, kW·h/kg, K_j is CO_2 emission factor for energy category j, $kgCO_2/kg$ or $kgCO_2/(kW \cdot h)$.

(3) NAC and RAC transportation phase

CO_2 emissions from transportation of concrete to the construction site (C3), the corresponding calculation formula is shown in Eqn (4):

$$C3 = M \times D \times ET, \tag{4}$$

where C3 refers to the transportation CO_2 emissions from concrete manufacturing plants to the construction sites, $kgCO_2$; M is the total mass of 1 m^3 of concrete, and $M = \Sigma M_i$, kg; D is the distance for transporting concrete, km.

(4) NAC and RAC construction phase

The formation of concrete blocks is a major source of CO_2 emissions during the construction phase (Li et al., 2011). Key data for the construction phase include auxiliary materials, construction losses, and energy consumption from machinery and equipment. The corresponding calculation formula is shown in Eqn (5):

$$C4 = \Sigma M_i \times EF_i + \Sigma e_j \times K_j, \tag{5}$$

where C4 refers to CO_2 emissions from the construction of concrete, $kgCO_2$.

(5) NAC and RAC carbonation absorption phase

1) Carbonation depth calculation

Alkaline substances in concrete chemically react with atmospheric CO_2, offering some environmental compensation by absorbing CO_2. In previous studies, carbonation effects were often ignored, or NAC absorption data were used to estimate RAC CO_2 emissions, leading to inaccuracies. In this paper, a carbonation depth prediction model was adopted according to Xiao and Lei (2008), and the corresponding calculation formula is shown in Eqn (6):

$$x_c = 839 g_{RC} \left(1-R\right)^{1.1} \sqrt{\frac{\left(\frac{W}{\gamma_c C}\right) - 0.34}{\gamma_{HD} \gamma_c C} n_0 t}, \tag{6}$$

where x_C represents the carbonization depth, m; R represents relative humidity; W is water consumption of 1 m^3 RAC, kg; C is the amount of cement used for 1 m^3 of RAC, kg; γ_C is the cement variety correction coefficient, assuming $\gamma_C = 1$; γ_{HD} represents the correction coefficient of cement hydration degree; if the curing periods are more than 90 days, then γ_{HD} is equal to 1; if the curing periods are 28 days, then γ_{HD} is equal to 0.85; and the values for intermediate curing periods determined through linear interpolation; n_0 represents the volume concentration of CO_2; t represents the carbonization absorption time, year; g_{RC} represents the impact coefficient of RAC, which is equal to 1 when the substitution rate is 0, and then increases to 1.5 if a 100% substitution rate, and likewise, intermediate substitution rates are determined through linear interpolation.

2) Carbon absorption by carbonation of concrete

Carbonation depth indicates the extent of concrete carbonation: the greater the depth over the same period, the faster the carbonation rate and the higher the CO_2 absorption. The corresponding calculation formula of carbonization absorption C5 is shown in Eqn (7):

$$C5 = 0.044 m_0 \frac{V_c}{V_0} = 0.044 m_0 \frac{x_c A_{surface}}{1}, \tag{7}$$

where m_0 measured the absorption of carbon when fully carbonized, mol/m^3 (Li, 2009); x_C is the carbonation depth, m; V_C and V_0 represent the volume of concrete and, the total volume of concrete, respectively, m^3; $A_{surface}$ is the exposed surface area of concrete, m^2.

(6) NAC and RAC demolition phase

Since RAC is still in the development stage, secondary recycling can be temporarily disregarded. In the demolition phase (C6), CO_2 emissions mainly result from demolition activities, waste concrete transport, and landfilling:

1) Estimating energy consumption for demolition is challenging; however, this study assumes it is approximately 90% of the energy required for construction (Gong et al., 2012), the corresponding calculation formula is shown in Eqn (8):

$$C6a = 0.9C4, \tag{8}$$

where C6a is CO_2 emissions for the demolition phase of concrete, $kgCO_2e$.

2) According to Eqn (4), CO_2 emissions from the transport energy consumption of the waste concrete (C6b) are calculate.

3) The landfill process for concrete is calculated as:

$$C6c = \Sigma M_i \times EL, \tag{9}$$

where C6c is CO_2 emissions from landfill of concrete, $kgCO_2$; EL is CO_2 emission factor of the landfill process, $kgCO_2$/kg.

3.1.4. Inventory data

The data in this study were primarily gathered from standards, specifications, literature, field research, and experiments.

(1) Raw material production and transportation

1) Raw material production

CO_2 emissions from raw material production are determined by the CO_2 emission factor and material quantity. The CO_2 emission factor is sourced from GB/T 51366-2019 "Construction Carbon Emission Calculation Standard" (Ministry of Housing and Urban-Rural Development, 2019). In the absence of specific data, recent literature statistics were used. The carbon emission factors of recycled concrete materials are listed in Appendix, with the recycled aggregate concrete factor being 0.0017 $kgCO_2$/kg (Guo et al., 2018). CO_2 emissions from the raw material production phase are summarized in Table 2.

2) Raw material transportation

Raw materials are transported to concrete mixing plants, and the carbon footprint of this process is significant. Since raw materials come from different locations, transport distances vary and play a key role in determining CO_2 emissions during transportation. Due to over-extraction of natural sand and gravel and environmental protection measures, quarries near cities are scarce. As a result, natural aggregates must be mined and transported from more distant suburban areas, which is 4-8 times the distance of recycled concrete aggregate transport (Tošić et al., 2019). Freight transport distances and CO_2 emission factors are presented in Appendix.

(2) NAC and RAC manufacturing

CO_2 emissions from recycled aggregate concrete (RAC) production primarily result from mechanical energy use. Xiao et al. (2016) found that producing 1 m^3 of RAC requires 2.0 kW·h of electricity. Based on IPPC and other literature, this study sets the CO_2 emission factor for electricity at 0.88 $kgCO_2$/kW·h (Martínez-Lage et al., 2020; Xiao et al., 2016).

(3) NAC and RAC transportation

Recycled aggregate concrete is transported to construction sites using 30-ton heavy-duty diesel trucks, with a CO_2 emission factor of 0.078 $kgCO_2$/t·km. The transport distance is set at 40 km according to the Construction Carbon Emission Calculation Standard (GB/T 51366-2019) (Ministry of Housing and Urban-Rural Development, 2019).

(4) NAC and RAC construction

Recycled concrete was used to produce paving bricks for expressway slope projects. No mechanical or auxiliary material consumption was required for laying the ecological bricks in this project. Therefore, the construction phase refers only to the process of converting recycled concrete into ecological bricks, with attention only to material loss (Li et al., 2011). In this study, the material loss rate for RAC is set at 2%, and the results are summarized in Table 2.

(5) NAC and RAC carbonation absorption

During carbonation, with an ambient relative humidity of 52% in Shandong and an ambient CO_2 concentration of 0.034%, RAC is cured for 28 days, with a concrete service life of 50 years, the exposed surface area of 1m^3 RAC, namely $A_{surface}$ = 5.68 m^2 (Lee et al., 2013). And finally, the CO_2 absorbed by RAC during the carbonation phase is shown in Table 2.

(6) NAC and RAC demolition

During the demolition stage, CO_2 emissions are calculated using Eqns (8)–(9). Waste concrete is transported to a landfill, with an average distance of 30 km. The CO_2 emission factor for landfill, as indicated by Xiao et al. (2016), is 1.055 kg CO_2/kg. CO_2 emissions from the demolition phase are detailed in Table 2. Results indicate that RAC produces lower CO_2 emissions than NAC at the same WCR. Additionally, the optimal mix for minimizing CO_2 emissions in recycled concrete is RAC-100b, which was used to manufacture paving bricks for the slope projects.

3.2. Shape design options of RAC

3.2.1. Design of recycled concrete structural members

Existing studies on concrete shape design focus on mechanical properties and stability (Chea et al., 2024; Cai & Liu, 2023; Choi et al., 2024). However, few studies address shape optimization of recycled concrete for carbon emission reduction. To meet the strength requirements of recycled concrete, three basic structural member shapes are designed: hexagonal prism, cube, and cylinder. The shape optimization process for recycled

Table 2. CO_2 emissions of 1 m^3 8 types of concretes with different recipe (Unit: $kgCO_2$)

Types	C1a	C1b	C2	C3	C4	C5	C6	C7
NAC[a]	290.8491	57.9920	1.7686	7.4880	7.1620	0.1339	17.0608	382.1864
RAC-30[a]	290.6774	49.3916	1.7686	7.4880	6.9865	0.1540	16.9906	373.1487
RAC-50[a]	290.5629	43.6580	1.7686	7.4880	6.8696	0.1607	16.9438	367.1302
RAC -100[a]	290.2768	29.3240	1.7686	7.4880	6.5771	0.1674	16.8269	352.0940
NAC[b]	243.2233	58.1499	1.7686	7.4880	6.2126	0.2245	16.6810	333.2990
RAC-30[b]	243.0455	49.2415	1.7686	7.4880	6.0309	0.2581	16.6083	323.9247
RAC-50[b]	242.9269	43.3026	1.7686	7.4880	5.9097	0.2694	16.5599	317.6864
RAC-100[b]	242.6305	28.4553	1.7686	7.4880	5.6068	0.2806	16.4387	302.1074

Notes: C7 = C1a + C1b + C2 + C3 + C4 – C5 + C6.

concrete structural members, integrating project-specific characteristics and sponge-like functional requirements, comprises the following three-step design methodology: 1) Diagonal Segmentation: A complete recycled concrete structural member is bisected along a 45-degree diagonal plane, either through its vertical facade or horizontal cross-section, to save materials and reduce carbon emissions. 2) Hollow Structural Configuration: The member is designed with an internal hollow cavity to optimize material efficiency while maintaining load-bearing capacity. 3) Serrated Edge Profiling: Cutting edges are engineered with a sawtooth morphology to enhance the stability. 4) As shown in Figure 4, the shape optimization process is applied into the all geometric variants, including cylinder, regular hexagonal prism, regular quadrangular prism[1], regular quadrangular prism[2]. The optimized design of recycled concrete structural members offers the following advantages. First, cutting the structural member into two halves saves building materials and reduces carbon emissions. Additionally, the zigzag cutting edge increases friction between the structural member and the slope surface, enhancing stability. Furthermore, hollow structural members can be filled with vegetation to absorb carbon dioxide. Based on the experimental tests in Table 3 and literature (X. Zhang & X. Zhang, 2021; Alvarez et al., 2022), the properties of four recycled concrete structural member shapes are compared and summarized in Table 4.

3.2.2. Manufacturing process of recycled concrete structural members

In accordance with China's national standard for ready-mixed concrete (GB/T 14902-2012) (General Administration of Quality Supervision, Inspection and Quarantine, & Standardization Administration of the People's Republic of China, 2012) and related specifications, C40 waste concrete is used as the raw material, and wooden templates are first created for the recycled concrete structural members. Wooden strips are then used to reinforce the model, followed by grouting the prefabricated parts of the recycled concrete structural members. After several attempts, the qualified recycled concrete structural members were finally completed. The manufacturing process and samples of recycled concrete structural members are shown in Figure 5 and Figure 6, respectively.

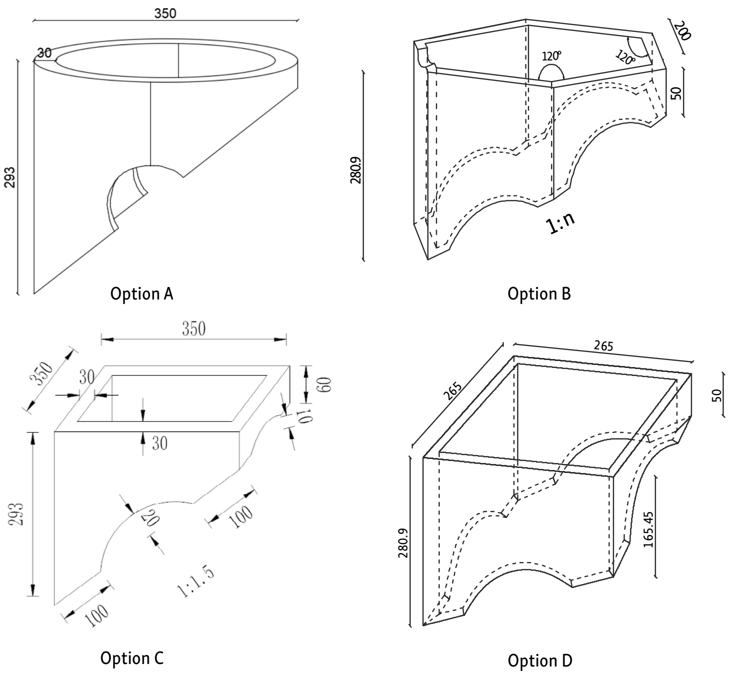

Figure 4. Recycled concrete structural member shape options

Table 3. RAC Consumption for four shape options of recycled concrete structural members

Shape design	Cylinder	Regular hexagonal prism	Regular quadrangular prism[1]	Regular quadrangular prism[2]
Definition	Option A	Option B	Option C	Option D
Quantity of bricks/ Unit RAC (1 m^3)	261.98	194.60	389.86	161.24

Notes: Option C represents the ones are cut along a face diagonal line, and Option D represents the ones are cut along a body diagonal line.

Table 4. Comparisons of different shape options of recycled concrete structural members

Items	Material saving amount	Carbon emissions reductions	Stability
Order of Options	C > A > B > D	C > A > B > D	A > B > D > C

a) b) c) d)

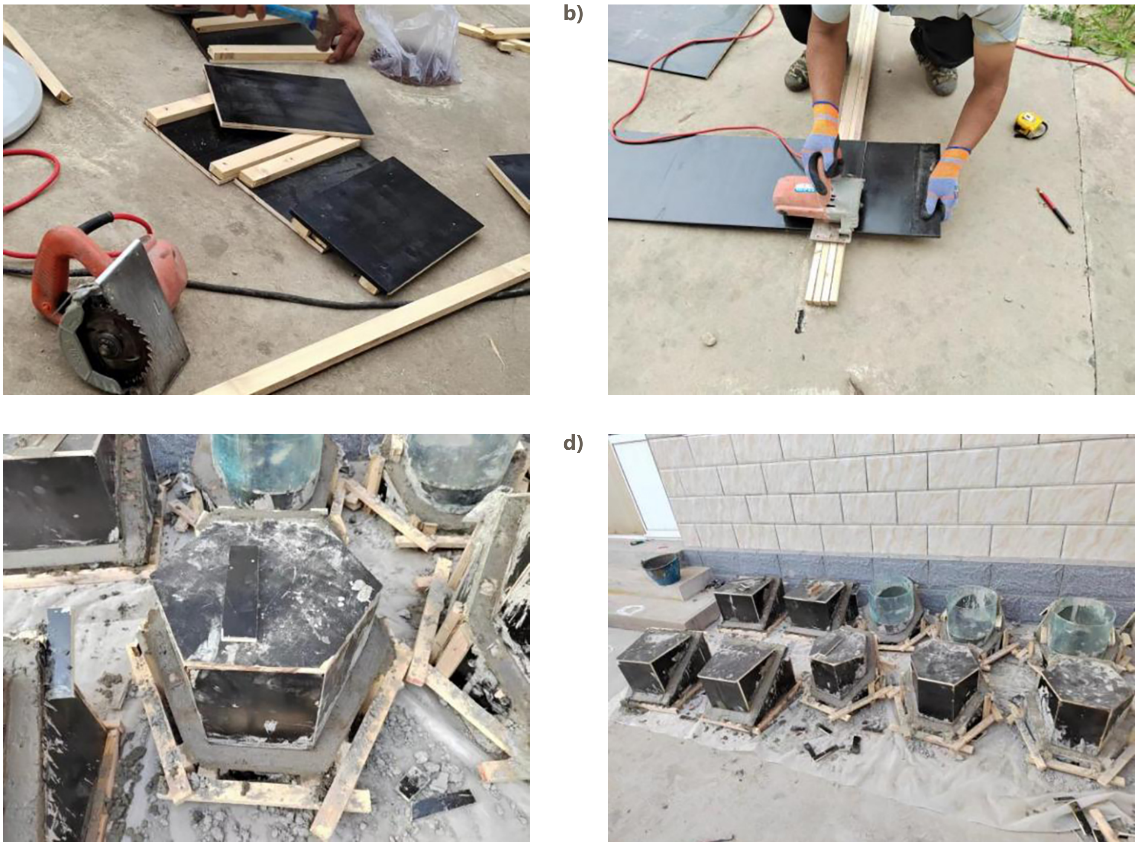

Figure 5. Production process and models of recycled concrete structural member

Figure 6. Samples of finished recycled concrete structural member

Table 5. Test area for the slopes

Start and end post No.	Position	Height (m)	Protection length (m)	Area (m^2)	C30 concrete block (m^3)
K58+820.0 ~ K59+065.1	Right	7.1	245.1	5083.98	101.79
DK0+146.0 ~ DK0+280.0	Right	5.7	121		38.44

4. Case study

4.1. Project overview

The G35 (Jinan-Guangzhou) Expressway is a major north-south corridor in China. The Shandong section spans from Jinan to Heze, covering approximately 335 kilometers. In the Ji-He Road reconstruction and expansion project, slope projects were chosen to test recycled concrete. Relevant data are provided in Table 5.

4.2. Consumption of recycled concrete structural member for the slope project

Based on a slope rate of 1:1.5 and experimental results, material consumption for each shape was determined, as shown in Table 6.

Table 6. RAC consumption for different recycled concrete structural members

Options of shape	Option A	Option B	Option C	Option D
Number of bricks/ Unit slope area	14.15	8.01	11.11	11.11
Slope area/ Unit RAC	18.52	24.31	35.09	14.51

4.3. Analysis of CO_2 emissions of recycled concrete structural member for slope projects

An LCA-based CO_2 emission model was used to analyze the life cycle emissions of slope projects using RAC. The analysis evaluated four design options for RAC-100 structural members, and the comparative results are presented in Figure 7.

Figure 7 shows that the most optimal option is the regular quadrilateral prism^2 paving bricks, which result in the lowest CO_2 emissions for slope projects over the life cycle. However, expert interviews and literature analysis reveal that while the regular hexagonal prism has slightly higher CO_2 emissions than the regular quadrilateral prism^2, it offers significantly greater stability (Cai & Liu, 2023), as shown in Table 4. Thus, the final choice was the regular hexagonal prism recycled concrete structural member. The life cycle CO_2 emissions of the slope test project using RAC amounted to 63.18 tCO_2, saving 6.52 tCO_2 compared to NAC, with a carbon reduction rate of approximately 9%. The RAC structural member and its laying effects in the test area are shown in Figure 8.

Existing studies suggest that synthesized biomass RAC can reduce CO_2 emissions by 2% compared to NAC (Ni et al., 2022). Additionally, Xiao et al. (2023) compared the

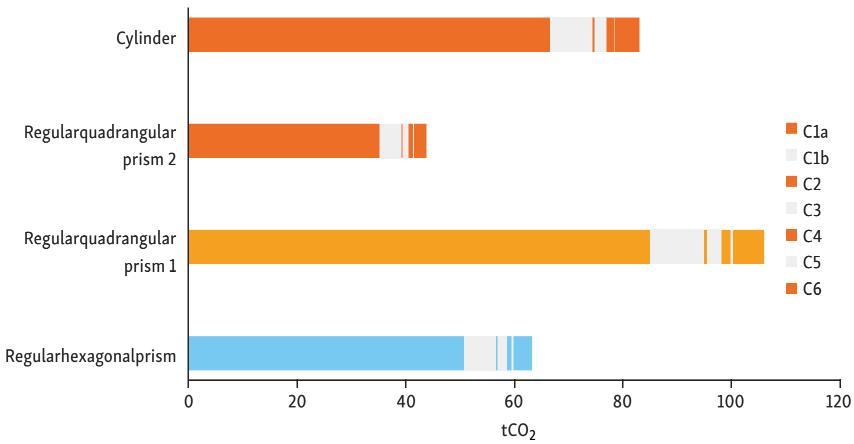

Figure 7. CO_2 emissions of the slope projects under 4 shapes options

Figure 8. The outcome of slopes projects of G35 (Jinan-Guangzhou) Expressway

CO_2 emissions of buildings constructed with NAC and RAC. They found that Building A, which used RAC, reduced CO_2 emissions by 1.75% compared to Building B, which used NAC.

5. Results and discussions

5.1. Contributions of CO_2 emissions in NAC and RAC

Based on Table 2, raw material production (C1a) and transportation (C1b) are the primary contributors to CO_2 emissions in both NAC and RAC, consistent with the findings of Xiao et al. (2021) and Sabău et al. (2021). The results are also similar to those of concretes with a water-to-cement ratio of 0.5. For NAC, CO_2 emissions from raw material production (C1a) account for 72.97% to 76.10%, while for RAC, they range from 75.03% to 82.44%. According to accounting methods in the literature (Wu et al., 2023; Wan et al., 2003; Xu et al., 2004), excluding the impact of raw material transport, the CO_2 emissions of RAC may be underestimated by 17–25%. In this study, transportation CO_2 emissions from both raw materials to manufacturing (C1b) and recycled concrete to construction sites (C3) account for approximately 10% to 17% of the life cycle CO_2 emissions of RAC. For NAC, transportation CO_2 emissions from raw materials to manufacturing (C1b) and concrete to construction sites (C3) account for approximately 17% to 19%. CO_2 emissions during the recycled concrete manufacturing stage (C2) show minimal differences due to the similarity in production processes for both types of concrete. Additionally, CO_2 emissions from non-production stages (C3–C6) account for 8.33% to 17.45%, showing little difference between RAC and NAC.

5.2. The reasons of CO_2 emission reduction of RAC for the slope project application

From the above analysis, it is clear that shape design significantly impacts CO_2 emission reduction in slope projects. This is because shape design and optimization reduce embodied carbon through lower material consumption and increase carbon absorption by exposing more surface area. Additionally, the potential for CO_2 sequestration by vegetation planted in the hollow paving bricks will be explored. Furthermore, life cycle CO_2 emissions reductions in RAC applications are also attributed to design optimizations in the recipe, such as the recycled coarse aggregate replacement rate, water-cement ratio, transport distance, and carbonation absorption.

At a constant WCR, as the RCARR increases from 0% to 100%, the life cycle CO_2 emissions of RAC decrease. Specifically, the emissions are approximately 97.19%, 95.32%, and 90.64% of those of NAC, respectively, as shown in Figure 9a. This is primarily due to the fact that recycled concrete aggregate avoids the energy consumption associated with natural aggregate mining. Additionally, studies have shown that the CO_2 emission factor of recycled aggregate is lower than that of natural aggregate (Xiao et al., 2021). However, a RAC with a higher RCARR and similar strength to NAC may require additional cement or superplasticizers (González-Fonteboa & Martínez-Abella, 2008). Both cement and superplasticizers increase the CO_2 emissions of RAC (Nakic, 2018; López Gayarre et al., 2016). Therefore, CO_2 emissions from raw material acquisition depend on several factors.

Second, when the RCARR is fixed at 0%, 30%, 50%, or 100%, the life cycle CO_2 emissions decrease as WCR increases (a: W/C = 0.5, b: W/C = 0.6), as shown in Figure 10. This aligns with the findings of Xu et al. (2004). The reduction in CO_2 emissions is mainly due to the increase in recycled concrete aggregate use, which lowers the amount of cement required, a material with a higher carbon factor.

Recycled aggregate is subject to minimal geographical restrictions, as aggregate processing plants can be located near concrete production sites, significantly reducing transport energy consumption. In this study, CO_2 emissions during the transport phase of RAC raw materials are reduced by 15% to 51% compared to NAC. However, if the transport distance of recycled aggregate exceeds a certain threshold, the life cycle CO_2 emissions of RAC will surpass those of NAC. Therefore, a sensitivity analysis was conducted on the distance from the aggregate processing plant to the recycled concrete manufacturing plant.

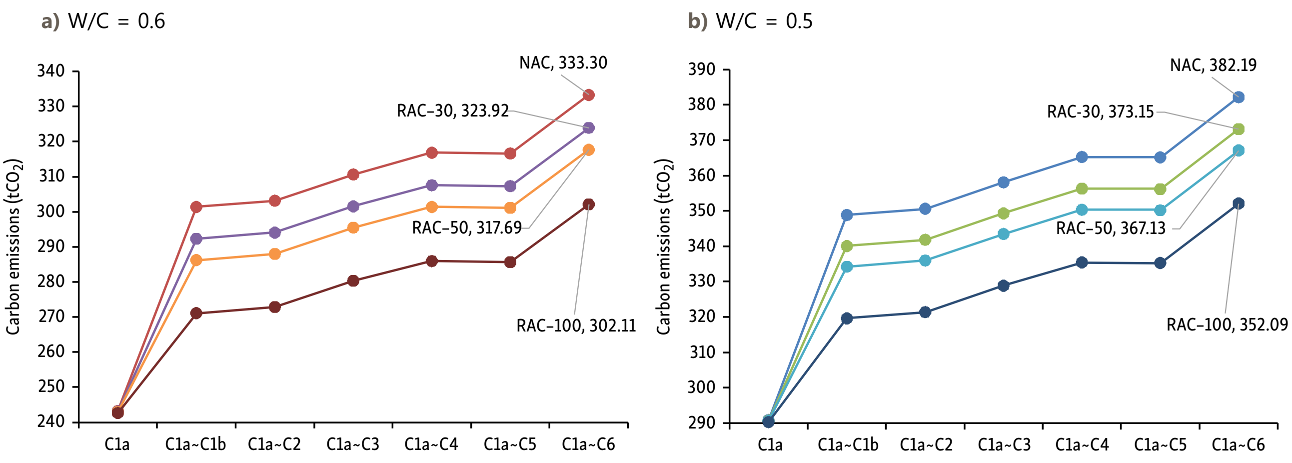

Figure 9. Effects of RCARR on CO_2 emissions of concretes

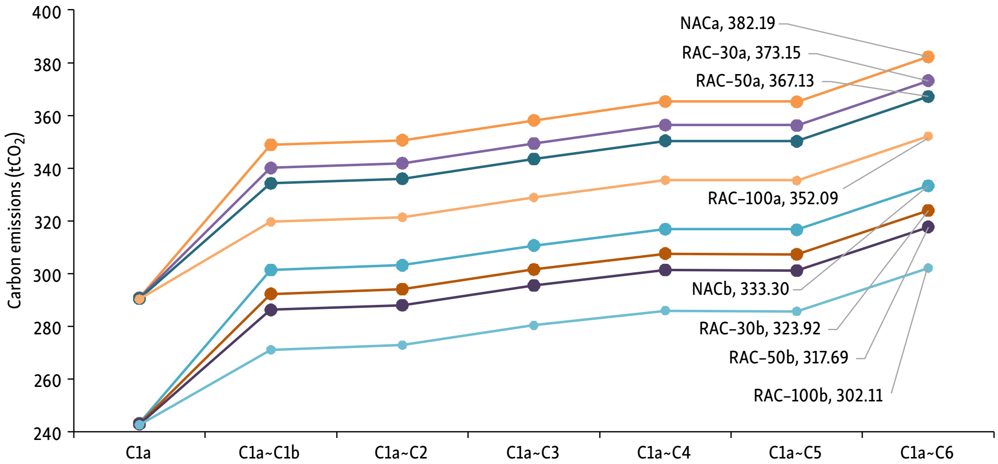

Figure 10. Effects of WCR on CO_2 emissions of concretes

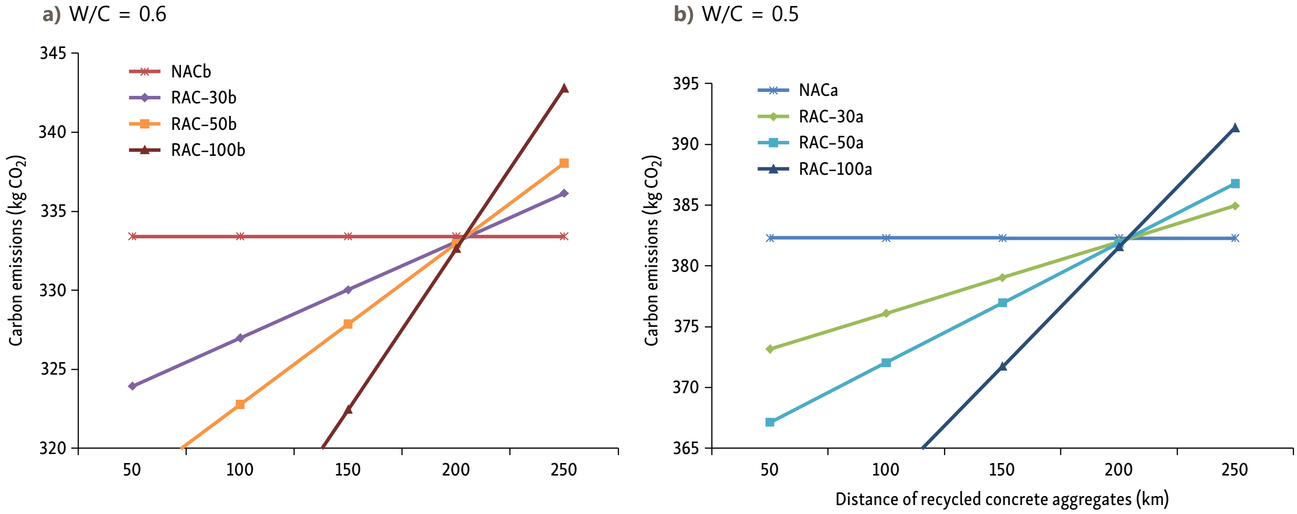

Figure 11. Relationships between transport distance of recycled concrete aggregates and CO_2 emissions

Currently, there is no large-scale production of recycled aggregates in China, and the number of recycled aggregate processing plants is limited (Lei et al., 2022). Specifically, this study examines four additional transport distance scenarios (100 km, 150 km, 200 km, and 250 km) based on the original 50 km. The results show that the life cycle CO_2 emissions of RAC increase, as depicted in Figure 11. Based on the results, it can be concluded that, under the same RCARR and WCR, as transport distance increases, life cycle CO_2 emissions will transition from negative to positive growth. As the transport distance increases, its impact on life cycle CO_2 emissions grows. The sensitivity analysis results reveal a critical threshold for the transport distance of recycled concrete aggregate. For the projects considered in this paper, when the transport distance from the recycled aggregate processing plant to the recycled concrete manufacturing plant exceeds approximately 204.2 km, the life cycle CO_2 emissions of RAC will surpass those of NAC.

Previous studies generally did not account for CO_2 absorption through carbonation during the life cycle of concrete (Guggemos & Horvath, 2008; Flower & Sanjayan, 2007; Vieira & Horvath, 2008). Ignoring this carbonation effect tends to overestimate CO_2 emissions. This study considers carbonation absorption for both NAC and RAC, and the results show that CO_2 absorption in RAC increases by approximately 15% to 25% compared to NAC. Specifically, as RCARR increases at a constant WCR, or as WCR increases at a constant RCARR, the carbonation absorption of RAC is enhanced, consistent with the findings of Xiao et al. (2021). Therefore, RAC utilization not only reduces CO_2 emissions but also enhances carbonation absorption, making it a crucial strategy for achieving low-carbon development in the construction industry. Furthermore, regarding the difference caused by carbonation absorption, as RCARR increases, the influence coefficient of recycled concrete aggregate increases, leading to greater CO_2 absorption. Additionally, the amount of carbonation absorption depends on factors such as storage time, exposure area to air, and other characteristics of RAC (Xiao et al., 2021; Yang et al., 2014).

5.3. Recommendation

Based on the findings and analyses, the following recommendations are proposed. First, under the constraints of RAC strength and durability, increasing the proportion of recycled concrete aggregate and locating aggregate manufacturing plants near concrete production sites are effective strategies for reducing CO_2 emissions in RAC applications. The acquisition and transport of raw materials are key factors in the CO_2 emissions reduction of RAC compared to NAC. To meet the required strength of RAC, recycled concrete aggregate should replace natural aggregate as much as possible. Additionally, aggregate manufacturing plants should be located as close as possible to concrete production sites to minimize transport energy consumption and CO_2 emissions. Furthermore, there is a maximum transportation distance threshold beyond which the CO_2 emissions of RAC exceed those of NAC. Second, the smaller the particle size of crushed waste concrete, the larger the exposed area, and consequently, the greater the carbon absorption capacity of RAC. The particle size of waste concrete significantly impacts the carbon sequestration of RAC due to the strong correlation between particle size distribution and exposed area. When using waste concrete to prepare paving bricks and other components, aggregates should be crushed finer to enhance the carbon sequestration capacity. Third, it is feasible to consider shape design and optimization of RAC applications, such as paving bricks, from the perspectives of stability and CO_2 emission reduction. This design reduces embodied carbon from material consumption and enhances carbonation absorption by increasing the exposed surface area. In the near future, the CO_2 sequestration potential of vegetation planted on hollow paving bricks will be explored.

6. Conclusions

This study develops a CO_2 emission accounting model for concrete using the Life Cycle Assessment (LCA) method. CO_2 emissions per unit volume of NAC and RAC, influenced by two WCRs and four RCARRs, are estimated as 382.19, 373.15, 367.13, 352.09, 333.30, 323.92, 317.69, and 302.11 kgCO_2e, respectively. Four shape options for the RAC structural members were designed, optimized, and compared. A case study of slope projects on the G35 Expressway was conducted to analyze CO_2 emissions under different RAC structural member shape designs. Finally, the regular hexagonal prism (Option B) design was adopted for the slope projects, resulting in 63.18 tons of CO_2 emissions, which is 6.52 tons less than NAC, yielding a carbon reduction rate of approximately 9%. In addition, there is a transport distance threshold of approximately 201.7 km, beyond which the life cycle CO_2 emissions of RAC exceed those of NAC from the recycled aggregate processing plant to the recycled concrete manufacturing plant.

The study findings indicate that, based on life cycle CO_2 emissions, raw material production and transportation are the top two contributors to CO_2 emissions for both NAC and RAC. The results also show that, in addition to shape design, other factors contributing to life cycle CO_2 emissions reduction in RAC applications include recycled coarse aggregate replacement rate, water-cement ratio, transport distance, and carbonation absorption. Specifically, the similar carbon emission reduction effects between the natural and recycled concretes include that: 1) The raw materials production and transportation are the two main contributors to the life cycle carbon dioxide emissions of both NAC and RAC. 2) The life cycle carbon emission decreases with the increase of water-cement ratio and recycled concrete aggregates replacement rate, respectively. 3) According to carbon dioxide emissions and stability comprehensively, the regular hexagonal (Option B) paving brick was finally selected for the slope test projects. The difference in carbon emission reduction effects between the natural and recycled concretes include that: 1) The life cycle carbon dioxide emissions of RAC range from 97.64%~ 90.64% of that of NAC. 2) Compared to the NAC, the key processes of carbon emission reduction of RAC include the raw material acquisition and transportation stage as well as the carbonization absorption stage. 3) There is a transport distance threshold, beyond which the life cycle CO2 emissions of RAC exceed those of NAC through sensitivity analysis.

This study presents the following recommendations: (1) under the constraints of RAC strength and durability, increasing the proportion of recycled concrete aggregate and locating aggregate manufacturing plants near concrete production sites are effective ways to reduce CO_2 emissions from recycled concrete; (2) smaller particle sizes of crushed waste concrete result in larger exposed areas, thus enhancing carbon absorption in RAC; and (3) it is feasible to optimize the shape design of RAC applications for stability and CO_2 emissions reduction. Based on this study, further research could explore the potential for CO_2 emissions reduction through carbon sequestration by vegetation planted on slope projects. Additionally, the cost-benefit analysis of energy-saving technologies in the life cycle of slope projects could be assessed in future studies.

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Author contributions

Wein Zhu: Methodology, Data analysis, results discussion, Writing – Original draft; Jianing Li: Data collection, Data analysis, Methodology; Writing – Original draft; Linghan Wang: Data collection, Data analysis, Methodology; Xiaodong Li: Supervision; results discussion, Writing – Reviewing and Editing.

Disclosure statement

The authors declare that they have no know competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX

Table A1. CO_2 emission factors at the raw material production stage

Raw materials	Water	Cement	Natural aggregate	Recycled concrete aggregate	Sand
CO_2 emission factors ($kgCO_2/kg$)	0.000168	0.735	0.00218	0.0017	0.00251

Table A2. Distance and transport CO_2 emission factors for raw materials

	Cement	Natural aggregate	Recycled concrete aggregate	Sand
Transport distance (km)	150	200	50	100
Transport CO_2 emission factors / [$kgCO_2/(t\cdot km)$]	0.162	0.162	0.162	0.162