Carbon emission modeling and analysis of building materialization process

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Abstract: The environmental properties of building assembly and recycled concrete are becoming highly related to the theme of the construction industry developments. Therefore, in order to account for the reduction effect of greenhouse gas arising from the combination of such two techniques, the building materialization process is divided into fabrication stage, transport stage, and site operation stage, and the calculation model for the assembled monolithic recycled concrete structures, ordinary assembled monolithic concrete structures, and cast-in-place concrete structures is established. Analyses and comparisons on the cases in Chongqing can be conducted owing to the model. The research results show that from the perspective of the entire materialization process, OAMCS can save 25.94% of carbon emissions compared to CCS per cubic meter of components, while AMRCS can further save 8.5% of carbon emissions compared to OAMCS per cubic meter of components, which can provide basic data for emission reduction and facilitate integration of the two techniques.

1. Introduction
In 2014, the 5th assessment report of IPCC stated the average global surface temperature was 14.6℃, which was 0.69℃ higher than that of the 20th century[1]. The only solution to global warming is to reduce greenhouse gas emissions. As one of the economic pillars of China, the construction industry, which contributes to 36% of global carbon emissions, makes China shoulder a greater responsibility and mission of emission reduction[2].

Building assembly is a construction technique with which building components are prefabricated in a factory in advance, then transported to the site, and assembled eventually. It is being vigorously promoted in China and attracts the attention of more scholars thanks to significant advantages such as high efficiency and environmental protection.
C MAO et al. [3] calculated the carbon emissions of prefabricated buildings and cast-in-place buildings, and pointed out that the former had more advantages in terms of carbon emissions. Y GAO et al. [4] analyzed the carbon emissions of the whole construction process of assembled monolithic buildings and proposed suggestions to reduce the carbon emissions. However, most scholars fail to consider the recyclability of materials, which makes the calculation results not truly reflect the carbon emissions within materialization process. Meanwhile, some scholars failed to compare the carbon emissions of different structures based on the same calculation model and basic data, resulting in a lack of reference for the results. Therefore, it is necessary to analyze carbon emission based on the same calculation model and basic data and consider the material recovery.

In addition, as an essential material in the construction industry, concrete has accounted for 15% of China's total carbon emissions [5], so the application of recycled concrete is particularly important. Recycled concrete is a green building material using waste concrete to produce recycled aggregate and powder, thus partially replacing natural aggregate and cement in ordinary concrete. Z S WANG et al. [6] pointed out that multiple recovery could reduce carbon emissions and improve the value coefficient of concrete. J Z XIAO et al. [7] analyzed the carbon emissions of recycled concrete under different substitution rates of recycled coarse aggregate, and the results showed that the transport distance of recycled coarse aggregate and carbonization of recycled concrete had an important impact on the reduction of carbon emissions of concrete. However, most scholars have overlooked the contribution of recycled powder to reducing the carbon emission of concrete. As the component with the highest carbon emission in concrete, the content of cement has a crucial influence on the total carbon emission of concrete. Therefore, using recycled powder produced in the recycling process of waste concrete to replace part of the cement is bound to be of great benefit to the emission reduction.

In conclusion, the application of recycled concrete in the assembled monolithic buildings is not only feasible [8], but also further reduce the carbon emission of concrete production. In this paper, the carbon emission model of the materialization process is established and exploited to analyze cases adopting the three structures.

2. Assessment system of carbon emission

Life cycle assessment (LCA) is a method to evaluate the impact of a product on the environment from the perspective of its whole life cycle. LCA consists of four steps: determination of objectives and scopes, inventory analyses, impact assessments and interpretations of results.

2.1. Objective and scope

The research objective is to calculate carbon emissions in the materialization process of CCS, OAMCS and AMRCS, to explain the main differences of carbon emissions in the three structures and to analyze the main sources of carbon emission. 1m³ is selected as the functional unit for comparison. The system boundary of carbon emission calculation for CCS is shown in figure 1. Please note that only the whole process of concrete (from the production of raw materials to the site operation of components) is shown in figure 1. Different from concrete, steel bars and other materials only have three stages: raw material production, raw material transportation to the construction site and the site operation of components. For OAMCS and AMRCS, the system boundary of carbon emission calculation is shown in figure 2.

[Figure 1. The boundary of carbon emission analysis for CCS.]
2.2. Inventory analysis
Inventory analysis is data collection and collation. Through classified statistics of material consumption, mechanical consumption and transportation distance at each stage of the above three structures, carbon emission factors of various materials and energy can be collected into a unified life cycle inventory.

2.3. Impact assessment and result interpretation
Based on the life cycle inventory, the environmental impact of the product at each life cycle stage can be quantitatively calculated and evaluated in impact assessment. Then, the carbon emissions of each structure at different stages are compared vertically, and the carbon emissions of the three structures are compared horizontally.

3. Calculation model for each stage
The international energy agency (IEA) regulates that the quantitative calculation and analysis of carbon emissions should be conducted in terms of carbon dioxide equivalent. The building materialization process in its life cycle can be divided into production stage, transportation stage and site construction stage, which are represented by $D_F$, $D_T$ and $D_s$ respectively. Therefore, the carbon emission model is shown in equation (1):

$$D = D_F + D_T + D_s$$  \tag{1}

3.1. Carbon emissions in the production stage $D_F$
For OAMCS, the production stage is divided into three steps, i.e. raw material acquisition and processing, raw material transportation to the component prefabrication plant, and component making. The carbon emission of making components is regarding the energy consumption of machinery and equipment on the production line. For AMRCS, the production stage requires two additional steps, i.e. transportation of waste concrete to the processing plant and processing of waste concrete into recycled aggregate.

However, for CCS, there are three steps: raw material production, transportation and site operation. In addition, as commercial concrete is commonly used for construction at present, raw materials of concrete need to be first transported to the commercial concrete mixing plant, and then commercial concrete is transported to the construction site after the completion of concrete premixing.

The carbon emissions of CCS, OAMCS and AMRCS in the production stage can be expressed as the following equation (2), (3) and (4):

$$D_F = D_{F1} + D_{FII} + D_{FIII}$$  \tag{2}

$$D_F = D_{F1} + D_{FII} + D_{Fv}$$ \tag{3}

$$D_F = D_{F1} + D_{FII} + D_{Fv} + D_{FvI} + D_{FvII}$$ \tag{4}

Where, $D_{F1}$, $D_{FII}$ and $D_{FIII}$ respectively represent the carbon emissions of raw material acquisition and processing (except recycled aggregate), raw material transportation to concrete mixing plant and production of premixed concrete in the plant; $D_{Fv}$ and $D_{FvI}$ respectively represent the carbon emissions of transport of raw materials to the component prefabrication plant and the components making (including concrete mixing and steel bar processing, etc.); $D_{FvI}$ and $D_{FvII}$ respectively represent the carbon emissions of transportation of waste concrete to recycled aggregate processing plant and
processing of waste concrete into recycled aggregate. $D_{Fi}$ is the product of component volumes and carbon emission factors of component prefabrication; Similarly, $D_{Fi\text{vii}}$ is the product of the mass of recycled materials (including recycled aggregate and recycled powder) and the carbon emission factor of recycled material production.

3.1.1. Raw material production.

\[ D_{Fi} = \sum_{i=1}^{n} d_i \times e_i \times (1 - \alpha_i) \]  

Where, $d_i$ is the consumption of the $i^{th}$ raw material; $e_i$ is the carbon emission factor of the acquisition, production and processing of the $i^{th}$ raw material, and $\alpha_i$ represents the recovery coefficient of the $i^{th}$ material. For reinforcement bars, $\alpha_i = 0.4$; For ordinary steel, $\alpha_i = 0.8$; For aluminum, $\alpha_i = 0.85$; For other materials, $\alpha_i = 0[1]$. The calculation method of $D_{Fi\text{v}}$ is the same as the above equation, and $\alpha_i = 0$.

3.1.2. Raw material transportation.

\[ D_{Fi\text{iv}} = \sum_{i=1}^{n} m_i \times t_i^{-1} \times k_i \times v_i \times r \times 100^{-1} \]  

Where, $m_i$ is the mass of the $i^{th}$ material; $t_i$ is the carrying capacity of the conveyance for the $i^{th}$ material; $k_i$ is the transport distance of the $i^{th}$ material; $v_i$ is the carbon emission factor converted from the fuel consumption per 100 km of the transport vehicle of the $i^{th}$ material; $r$ represents the no-load return coefficient, and $r=1.67[9]$. $D_{Fi\text{iv}}, D_{Fi\text{v}}$ and $D_{Fi\text{vi}}$ are all calculated by equation (6).

3.1.3. Component prefabrication. The prefabricated components are manufactured in the components prefabrication plant and energy consumption statistics can be readily carried out. Therefore, the output and energy consumption of various components in a certain period of time can be measured to obtain the energy consumption per unit volume of various components.

\[ D_{Fi\text{vii}} = \sum_{i=1}^{n} V_i \times (C_{id} \times N_d + C_{ig} \times N_g + C_{ie} \times N_e) \]  

Where, $V_i$ represents the volume of the $i^{th}$ component; $C_{id}, C_{ig}$ and $C_{ie}$ represent the consumption of diesel, gasoline and electricity for per cubic meter of the $i^{th}$ component; $N_d, N_g$ and $N_e$ respectively represent the carbon emission factors corresponding to diesel, gasoline and electricity.

3.2. Carbon emission in transport stage $D_T$

For CCS, carbon emissions during transportation represent transport carbon emissions of premixed concrete from commercial concrete plants to construction sites and other building materials such as steel bars from factories to construction sites.

For OAMCS/AMRCS, the prefabricated components need to be shipped to the construction site for assembly after completion in the prefabrication plant. In the practical transportation process of prefabricated components, different from bulk materials, the actual volume of components and the stacking mode on transport vehicles should be considered in addition to the weight of components themselves. However, considering the complexity of practical transportation, this paper assumes that the component mass just reaches the rated load of transportation vehicles during each trip.

\[ D_{Si} = \sum_{i=1}^{n} m_i \times t_i^{-1} \times k_i \times v_i \times r \times 100^{-1} \]  

Where, $m_i$ is the mass of the $i^{th}$ material; $t_i$ is the carrying capacity of the conveyance for the $i^{th}$ material; $k_i$ is the transport distance of the $i^{th}$ material; $v_i$ is the carbon emission factor converted from fuel consumption per 100km of the transport vehicle of the $i^{th}$ material; Similarly, the no-load return coefficient $r=1.67$. 

3.3. Carbon emission in site operation stage $D_s$

For CCS, many types of machinery are used and the working face is large, which is not convenient for the statistics of the number of machine-teams and the production capacity per machine-team. Therefore, the bill of quantities can be referred to for statistics of the number of machine-teams. Then, through the theoretical calculation of mechanical energy consumption per machine-team and energy carbon emission factor, the gross carbon emission of each kind of machinery can be calculated, and the gross carbon emission of each kind of machinery can be added up to obtain the total carbon emission of CCS during the site operation stage. See equation (9) and (10) for the specific calculation process.

$$D_s = \sum_{i=1}^{n} f_i \times p_i$$  \hspace{1cm} (9)

$$p_i = q_i \times K_1 \times K_2 \times K_3 \times K_4 \times w_j$$ \hspace{1cm} (10)

In equation (9), $f_i$ refers to the quantity of machine-teams of the $i^{th}$ component; $p_i$ refers to the carbon emissions in each machine-team of the $i^{th}$ component. In equation (10), $q_i$ refers to the rated power of the machinery of the $i^{th}$ component, and $K_1$ represents the time utilization factor, which is generally 0.60~0.75. $K_2$ refers to the capacity utilization factor, which is generally 0.60~0.80; $K_3$ represents the fuel consumption coefficient of vehicle speed, which is generally 0.97~1.00; $K_4$ represents the fuel consumption factor, which is generally 1.03; $w_j$ refers to the carbon emission factor of energy used by construction machinery regarding the $i^{th}$ component. $K_3$, $K_4$ are only for machines using diesel or gasoline [10].

For OAMCS/AMRCS, there are fewer types of machinery, which is easy for statistics. The carbon emission factor for installation of unit volume prefabricated components is calculated by the number of machine-teams, mechanical energy consumption and production capacity within each machine-team.

Combined with the volume of various components and carbon emission factors of various energy sources, the carbon emission of OAMCS/AMRCS in the site operation stage can be calculated, and the equation is the same as equation (7).

3.4. Carbon emission factor

3.4.1. Carbon emission factor of raw material production. As per the investigation, the carbon emission factor of recycled coarse aggregate is 12.88kg CO$_2$-eq/t. Y XIAO et al. [11] used the Debin recycling treatment device for construction waste to conduct carbon emission statistics during the processing of recycled powder. The results showed that the carbon emission generated by the power consumption of the equipment system was 16.3kg CO$_2$/t. To dry the powder, the carbon emission from coal combustion is 32.5kg CO$_2$/t. Therefore, the production of recycled powder per ton produces 48.8kg of CO$_2$. In addition, according to the IPCC research report, the Ebalance database of Sichuan University and the research results of other scholars [4,6], the carbon emission factors required for carbon emission calculation can be summarized as table 1. Because of the low content of admixture, the carbon emission caused by its production and transportation is ignored.

| Category                  | Carbon emission factor | Category                  | Carbon emission factor |
|---------------------------|------------------------|---------------------------|------------------------|
| Portland cement           | 800 (kg CO$_2$-eq/t)   | Aluminum                  | 2267 (kg CO$_2$-eq/t)  |
| Gravel                    | 3.12 (kg CO$_2$-eq/t)  | Diesel oil                | 2.73 (kg CO$_2$-eq/L)  |
| Sand                      | 3.66 (kg CO$_2$-eq/t)  | Gasoline                  | 2.26 (kg CO$_2$-eq/L)  |
| Water                     | 0.90 (kg CO$_2$-eq/t)  | Electricity               | 0.78 (kg CO$_2$-eq/kw-h) |
| Reinforced bar            | 2617 (kg CO$_2$-eq/t)  | Concrete mixing           | 0.70 (kg CO$_2$-eq/t)  |
| Steel plate               | 2702 (kg CO$_2$-eq/t)  | Recycled coarse aggregate production | 12.88 (kg CO$_2$-eq/t) |
| PVC                       | 3.254 (kg CO$_2$-eq/kg)| Recycled powder production | 48.80 (kg CO$_2$-eq/t) |
| Polystyrene               | 4.487 (kg CO$_2$-eq/kg)| Construction waste landfill | 6.15 (kg CO$_2$-eq/t)  |
3.4.2. Transport distance and corresponding carbon emission factor. As per the investigation and study of engineering cases, the transportation vehicles adopted in the case analysis are all dump trucks (10t). After conversion, the carbon emission of this type of trucks per 100km is 68.25kg. Transport distances and corresponding carbon emission factors related to the calculation are shown in table 2. Since there is no practical case of AMRCs at present, the transport distance of item 9-11 is the average value provided by a recycled aggregate manufacturer in Chongqing.

| No. | Raw material /Component | Distance of OAMCS/A MRCS (km) | Distance of CCS (km) | Carbon emission (kg/trip) | Comment |
|-----|------------------------|-------------------------------|----------------------|--------------------------|---------|
| 1   | Natural gravel         | 200                           | 200                  | 136.50/136.50             | From the producing area to the precast component factory/the site |
| 2   | Sand                   | 50                            | 50                   | 34.13/34.13               | Ditto   |
| 3   | Cement                 | 30                            | 25                   | 20.48/17.06               | Ditto   |
| 4   | Reinforced bar         | 50                            | 50                   | 34.13/34.13               | Ditto   |
| 5   | Steel plate            | 50                            | 50                   | 34.13/34.13               | Ditto   |
| 6   | PVC                    | 50                            | 50                   | 34.13/34.13               | Ditto   |
| 7   | Polystyrene            | 50                            | 50                   | 34.13/34.13               | Ditto   |
| 8   | Aluminum               | 50                            | 50                   | 34.13/34.13               | Ditto   |
| 9   | Waste concrete         | 50                            | -                    | 34.13/-                   | From the demolished building to the recycled aggregate factory or the landfill |
| 10  | Recycled aggregate     | 25                            | -                    | 17.06/-                   | From the recycled aggregate factory to the precast component factory |
| 11  | Recycled powder        | 25                            | -                    | 17.06/-                   | From the recycled aggregate factory to the precast component factory |
| 12  | Precast component      | 30                            | -                    | 20.48/-                   | From the precast component factory to the site |
| 13  | Premixed C30 concrete  | -                             | 30                   | -20.48                    | From the concrete manufacturer to the site |

4. Empirical analysis
For CCS and OAMCS, two cast-in-place office buildings in Chongqing are selected as examples to calculate the total carbon emissions. The total land area is 12000m² and 33900m² respectively, and the total building area is 32000m² and 33900m² respectively. The structure are both the frame-shear wall structure. According to the research results of J Z Xiao et al. [12], in order to ensure eligible mechanical properties and durability of recycled concrete, the replacement rate of recycled powder should not exceed 30%. Therefore, the recycled concrete used by AMRCs replaces 100% natural coarse aggregate and 30% cement in C30 concrete used in OAMCS examples with recycled coarse aggregate and recycled powder respectively.

In the calculation of carbon emissions of CCS, in order to make it comparable with the other two structures, only the carbon emissions generated by the processing and installation of steel bars and formwork and concrete production and casting are considered.

4.1. Cast-in-place concrete structure (CCS)
The main component volumes of the superstructure are as follows: column 564.84m³, wall 249.67m³, beam 1285.02m³, plate 1091.00m³; A total of 3190.53 m³. Considering both the volume of reinforcement in the component and the loss rate of premixed concrete casting, the unit volume of component is close to the consumption of premixed concrete per unit volume. Therefore, in the calculation below, each 1m³ of component volume is considered as 1m³ of concrete consumption.

4.1.1. Carbon emissions in the production stage. The mix ratio of C30 ready-mixed concrete is provided by the commercial concrete plant of the project example, with 190kg of water, 500kg of cement, 1231kg of natural coarse aggregate and 479kg of sand in 1m³ of concrete. According to the equation (5) and (6), carbon emissions from the production and transportation of raw materials
contained in C30 premixed concrete per unit volume can be calculated respectively (table 3), that is, 437.97kg. On this basis, considering the carbon emission of concrete mixing, we can conclude that from the raw material production to the completion of concrete premixing, the carbon emission of each 1m³ of C30 premixed concrete is 438.67kg. Therefore, the production of 3190.53m³ of concrete is born with a total of 1399.59t carbon dioxide equivalent, and the production of 653.41t steel bars bring about 1025.98t of carbon equivalent. Rebars and concrete are the basic materials of beams, slabs, walls and columns, so the carbon emissions of other secondary materials are ignored. As a result, the carbon dioxide equivalent of production stage in the project instance is 2425.57t.

### Table 3. Carbon emissions of manufacturing and transporting of raw material in 1m³ of concrete.

| Category          | Raw material manufacturing (kg CO₂-eq) | Transport (kg CO₂-eq) | Total (kg CO₂-eq) |
|-------------------|----------------------------------------|-----------------------|-------------------|
| Water             | 0.17                                   | -                     | 0.17              |
| Cement            | 400.00                                 | 1.42                  | 401.42            |
| Gravel            | 3.84                                   | 28.06                 | 30.90             |
| Sand              | 1.75                                   | 2.73                  | 4.48              |
| Total             | 405.76                                 | 32.21                 | 437.97            |

4.1.2. Carbon emissions in transport stage. The mass of C30 concrete per cubic meter is 2360kg, the weight of 3190.53m³ of C30 concrete is 7529.65t, and the carbon emission of concrete during transportation is 25.75t. The total weight of the steel bars is 653.41t, and the carbon emission of the steel bars is 3.72t. Therefore, the carbon emission in the transportation phase is 29.47t.

4.1.3. Carbon emissions in site operation stage. By referring to the construction organization plan and the bill of quantities of the project case, the specific types and model numbers of construction machines related to the reinforced concrete construction in the superstructure can be determined. Then, according to the rated power of construction machinery and using equation (10), the carbon emissions of each construction machine can be derived. Finally, according to formula (9), the carbon emission of CCS within site operation stage is 275.51t (table 4).

### Table 4. Carbon emissions in the site operation stage.

| Category                     | Model number | Carbon emission (kg CO₂-eq/machine-team) | Number of machine-team | Carbon emission (t) |
|------------------------------|--------------|------------------------------------------|------------------------|--------------------|
| Wheel crane                  | Lifting weight: 5t | 83.57                                    | 111.27                 | 9.30               |
| Tower crane                  | Lifting torque: 400kN·m | 96.22                                    | 817.88                 | 78.70              |
| Lorry                        | Capacity tonnage: 6t | 92.55                                    | 233.59                 | 21.62              |
| Single cage construction elevator | Lifting weight: 6t; Lifting height: 75m | 31.93                                    | 613.41                 | 19.59              |
| Rebar straightener           | Rebar diameter: 14mm | 9.28                                     | 167.56                 | 1.55               |
| Rebar cutter                | Rebar diameter: 40mm | 25.04                                    | 471.09                 | 11.80              |
| Rebar crimping machine      | Rebar diameter: 40mm | 9.99                                     | 416.18                 | 4.16               |
| Woodworking circular sawing machine | Diameter of saw disc: 500mm | 18.72                                    | 59.33                  | 1.11               |
| Threading machine           | Rebar diameter: 45mm | 18.72                                    | 713.60                 | 13.36              |
| AC arc welder               | Capacity: 32kV·A | 84.56                                    | 24.12                  | 2.04               |
| DC arc welder               | Capacity: 32kV·A | 75.55                                    | 731.01                 | 55.23              |
| Point welding machine       | Capacity: 75kV·A | 196.56                                   | 42.45                  | 8.34               |
| Butt welder                 | Capacity: 75kV·A | 196.56                                   | 138.76                 | 27.27              |
| Electroslag welder          | Magnitude of current: 1000A | 114.66                                   | 110.40                 | 12.66              |
| Welding rod dryer           | Size: 45×35×45 cm³ | 3.74                                     | 72.08                  | 0.27               |
| Concrete leveler            | Capacity factor: 5.5kw | 20.59                                    | 87.64                  | 1.80               |
| Concrete vibrator           | Capacity factor: 2.2kw | 8.24                                     | 232.80                 | 1.92               |
| Concrete pump               | HB60.13.90S; Capacity factor: 90kw | 352.80                                   | 13.57                  | 4.79               |
| Total                        |               |                                          |                        | 275.51             |
4.1.4. Summary. To sum up, the total carbon emission of CCS in the whole materialization process is 2,730.55 t. Therefore, for the whole materialization process, the carbon dioxide equivalent emitted from the formation of each 1 m³ of CCS components is 855.83 kg.

4.2. Ordinary assembled monolithic concrete structure (OAMCS)

4.2.1. Carbon emission in production stage. The mix ratio of C30 concrete for precast components is provided by the precast component factory, with 160 kg of water, 320 kg of cement, 1050 kg of natural coarse aggregate, 800 kg of sand and 1.50% of admixture in 1 m³ of concrete. As shown in Table 5, according to equation (5) and (6), the carbon dioxide equivalent generated by the production and transportation of raw materials in C30 concrete for each 1 m³ of precast components is 291.94 kg. On this basis, considering the carbon emission of concrete mixing, we can conclude that from the raw material production to the completion of concrete premixing, the carbon emission of each cubic meter of C30 concrete for precast components is 292.64 kg. Machinery on the assembly line of prefabricated components consumes electricity. Considering the material loss in component production, and according to equation (5), (6) and (7), the carbon emission generated by each 1 m³ of prefabricated components from the production of raw materials to the completion of component production is derived (Table 6).

| Ingredient         | Component    | Mass (t/m³) | Carbon emission (kg CO₂-eq) |
|--------------------|--------------|-------------|------------------------------|
| External wall       | Rebar        | 0.78        | 31.50                        |
| Internal wall       | Rebar        | 0.78        | 45.15                        |
| Shear wall          | Rebar        | 1.00        | 57.75                        |
| Superposed beam     | Rebar        | 1.00        | 5.78                         |
| Superposed slab     | Rebar        | 1.00        | 98.70                        |
| Stairway            | Rebar        | 1.00        | 48.51                        |

4.2.2. Carbon emission in transport stage. Based on the mass per unit volume of each component, the carbon emission of each 1 m³ of each component in the transportation stage is calculated (Table 7).

4.2.3. Carbon emission in site operation stage. After the components are shipped to the site, wheel cranes and tower cranes are used for assembly. The former consumes diesel, while the latter consumes electricity. According to the field measurement and conversion, the carbon dioxide equivalent emitted by the installation of various prefabricated components per unit volume is obtained (Table 8).
### Table 8. Carbon emissions of the site operation stage in 1 m³ of components.

| Component         | Electricity consumption (kw-h/m³) | Carbon emission (kg/m³) | Component         | Electricity consumption (kw-h/m³) | Carbon emission (kg/m³) |
|-------------------|-----------------------------------|------------------------|-------------------|-----------------------------------|------------------------|
| External wall     | 15                                | 11.70                  | Superposed beam   | 12                                | 9.36                   |
| Internal wall     | 15                                | 11.70                  | Superposed slab   | 12                                | 9.36                   |
| Shear wall        | 16                                | 12.48                  | Stairway          | 15                                | 11.70                  |

### 4.2.4. Summary. By consulting the bill of quantities, the volume of various components can be obtained. As shown in table 9, the carbon emissions of production stage, transportation stage and site construction stage are 1,765.29t, 24.16t and 33.66t, respectively. Therefore, the total carbon emission of the entire materialization phase of OAMCS is 1,823.10t. In terms of the whole materialization process, the carbon dioxide equivalent generated by each 1 m³ of OAMCS component is 855.83kg.

### Table 9. Overall carbon emissions of OAMCS.

| Component         | Quantity (m³) | Fabrication Stage (t CO₂-eq) | Transportation Stage (t CO₂-eq) | Site operation Stage (t CO₂-eq) | Total (t CO₂-eq) |
|-------------------|---------------|------------------------------|---------------------------------|---------------------------------|------------------|
| External wall     | 370.86        | 177.63                       | 2.54                            | 4.33                            | 184.51           |
| Internal wall     | 213.55        | 103.86                       | 1.46                            | 2.50                            | 107.82           |
| Shear wall        | 164.56        | 1095.78                      | 14.63                           | 20.54                           | 1130.95          |
| Superposed beam   | 75.54         | 47.67                        | 0.63                            | 0.71                            | 49.01            |
| Superposed slab   | 471.22        | 284.55                       | 4.03                            | 4.41                            | 292.98           |
| Stairway          | 99.74         | 55.80                        | 0.87                            | 1.17                            | 57.84            |
| Total             | 2876.52       | 1765.29                      | 24.16                           | 33.66                           | 1823.10          |

### 4.3. Assembled monolithic recycled concrete structure

#### 4.3.1. Carbon emission in production stage. Based on the concrete mix ratio of the OAMCS case, the concrete mix ratio of AMRCS components adopts recycled coarse aggregate and recycled powder to replace 100% of natural coarse aggregate and 30% of cement respectively, and are obtained through calculation and trial mixing. 1 m³ of concrete contains 187kg of water, 241kg of cement, 104kg of recycled powder, 1080kg of recycled coarse aggregate, 740kg of sand and 2.80% admixture. As shown in table 10, according to equation (5) and (6), carbon emissions from the production and transportation of raw materials contained in unit volume of recycled concrete can be calculated respectively, and the carbon dioxide equivalent generated by the production and transportation of raw materials in every 1 m³ of recycled concrete is 215.81kg. The preparation process of recycled concrete is basically the same as that of natural aggregate, so the carbon emission of concrete mixing is also set at 0.7kg CO₂-eq/m³. On this basis, considering the carbon emission of concrete mixing, we can conclude that from the raw material production to the completion of concrete mixing, the carbon emission of each cubic meter of recycled concrete is 216.51kg.

### Table 10. Carbon emissions of production and transporting of raw material in 1 m³ of recycled concrete.

| Category         | Raw material manufacturing (kg CO₂-eq) | Transport (kg CO₂-eq) | Total (kg CO₂-eq) |
|------------------|----------------------------------------|-----------------------|------------------|
| Water            | 0.17                                   |                       | 0.17             |
| Cement           | 192.80                                 | 0.82                  | 193.62           |
| Recycled powder  | 4.44                                   | 0.30                  | 4.74             |
| Recycled aggregate | 7.27                               | 3.08                  | 10.35            |
| Sand             | 2.71                                   | 4.22                  | 6.93             |
| Total            | 207.39                                 | 8.42                  | 215.81           |

The use of recycled coarse aggregate and recycled powder prevents waste concrete from being transported to landfills and buried. Therefore, avoided carbon emissions should be considered in the production and transportation of recycled aggregate and recycled powder, respectively, to show the contribution of recycled products to the environment. In the calculation process of table 10, the
carbon emission from the production of recycled coarse aggregate and recycled powder should deduct the carbon emission from waste concrete landfill, that is, the carbon emission factor for the production of recycled coarse aggregate is 6.73 kg CO2-eq/t, while the carbon emission factor for the production of recycled powder is 42.65 kg CO2-eq/t. In the calculation of the carbon emission of recycled coarse aggregate and recycled powder during transportation, the carbon emission of waste concrete from the demolished building to the landfill should be deducted, that is, the transport carbon emission factor of recycled coarse aggregate and recycled powder is 17.07 kg CO2/10t.

The method of prefabrication, type, quantity and material composition of components used in AMRCS carbon emission analysis are the same as those used in the OAMCS example. According to equation (5), (6) and (7), the carbon emission generated by each 1 m³ of prefabricated components from the production of raw materials to the completion of component production is derived (table 11).

### Table 11. Carbon emissions of the transport stage in 1 m³ of components.

| Component     | Rebar (kg) | Concrete (m³) | Steel plate (kg) | PVC (kg) | Polystyrene (kg) | Alumina (kg) | Electricity (kw-h) | Carbon emission (kg) |
|---------------|------------|---------------|------------------|----------|------------------|--------------|---------------------|----------------------|
| External wall | 132.60     | 0.78          | 31.50            | 0.50     | 1.43              | 4.08         | 15                  | 419.59               |
| Internal wall | 132.60     | 0.78          | 45.15            | 0.50     | 2.08              | -            | 13                  | 426.97               |
| Shear wall    | 204.20     | 1.00          | 57.75            | 0.50     | -                | -            | 18                  | 589.75               |
| Superposed beam | 204.00 | 1.00          | 5.78             | -        | -                | -            | 12                  | 554.86               |
| Superposed slab | 154.02 | 1.00          | 98.70            | 0.30     | -                | -            | 12                  | 527.72               |
| Stairway      | 142.80     | 1.00          | 48.51            | -        | -                | -            | 14                  | 483.36               |

4.3.2. Carbon emission in transport stage and site operation stage. Since the density of recycled concrete in 3.3.1 is basically the same as the density of natural aggregate concrete in 3.2.1, the carbon emission in AMRCS transport phase is considered to be the same as that in OAMCS transport phase in 3.2.2. Furthermore, AMRCS has the same number of components and installation as OAMCS engineering examples. Therefore, the carbon emission of the AMRCS site operation stage is the same as that of OAMCS site operation stage in 3.2.3.

4.3.3. Summary. As shown in table 12, the carbon emissions of production stage, transportation stage and site construction stage are respectively 1556.09t, 24.16t and 33.66t. Therefore, the total carbon emission of AMRCS in the whole materialization phase is 1613.90t. For the whole materialization process, the carbon dioxide equivalent generated by each 1 m³ of AMRCS component is 561.06 kg.

### Table 12. Overall carbon emission of AMRCS.

| Component     | Quantity (m³) | Fabrication Stage (t CO₂-eq) | Transportation Stage (t CO₂-eq) | Site operation Stage (t CO₂-eq) | Total (t CO₂-eq) |
|---------------|---------------|------------------------------|--------------------------------|--------------------------------|------------------|
| External wall | 370.86        | 155.61                       | 2.54                           | 4.34                           | 162.48           |
| Internal wall | 213.55        | 91.18                        | 1.46                           | 2.50                           | 95.14            |
| Shear wall    | 1645.62       | 970.50                       | 14.63                          | 20.54                          | 1005.67          |
| Superposed beam | 75.54 | 41.92                        | 0.63                           | 0.71                           | 43.26            |
| Superposed slab | 471.22 | 248.67                       | 4.03                           | 4.41                           | 257.11           |
| Stairway      | 99.74         | 48.21                        | 0.87                           | 1.17                           | 50.25            |
| Total         | 2876.52       | 1556.09                      | 24.16                          | 33.66                          | 1613.9           |

5. Result analysis

Among the three structures, the carbon emission in the production stage accounts for the largest proportion in the whole materialization process and plays an absolute leading role, which is 88.83%, 96.83% and 96.42% respectively. In the production stage, the material difference is the most fundamental element that causes the carbon emission difference of the three structures in the production stage. In addition, compared with CCS, OAMCS/AMRCS have fundamentally different
manufacturing processes for building components, which also leads to a large difference in carbon emissions generated by their component manufacturing. Therefore, this chapter will be divided into three dimensions, i.e. material, component production and the whole materialization process, to analyze the carbon emission differences of the three structures.

5.1. Dimension of material
The material dimension is divided into steel content and concrete production.

For reinforcement content, 204.80kg of reinforcement is contained in 1m$^3$ of components in CCS, while 179.30kg of reinforcement is contained in 1m$^3$ of components in OAMCS/AMRCS. The two projects are located in different locations in Chongqing, and their different external construction conditions are the main reason for the difference in steel content. In addition, CCS completes the production of components on the site, which is difficult to manage and less mechanized, and the quality of component molding is not easy to guarantee. In contrast, the construction of components of OAMCS or AMRCS is completed in the factory, which is more conducive to ensuring the quality of components, so the structural designer can reduce the safety factor appropriately. Lower safety means lower steel content.

Furthermore, for concrete production, carbon emissions per 1m$^3$ of concrete in CCS, OAMCS and AMRCS are 438.67kg, 292.64kg and 216.51kg, respectively. Based on the social willingness to pay theory, we can translate carbon emissions into environmental costs that more intuitively reflect their impact on the environment and society. According to literature [13], the environmental cost of CO$_2$ is 0.22 yuan /kg. Therefore, the environmental cost caused by carbon emission per 1m$^3$ of concrete in CCS, OAMCS and AMRCS is 96.51 yuan, 64.38 yuan and 47.63 yuan, respectively.

For CCS construction, concrete pumps are generally used for concrete conveying. Cement is used to lubricate the pipe wall when concrete is pumped. The amount of cement is directly related to the friction in the pipe and the degree of filling in the conveying cylinder when material is sucked. In addition, because the construction quality of components in CCS is more difficult to guarantee than that in OAMCS, laboratory personnel tend to use a smaller water-cement ratio in concrete mix design. Therefore, CCS requires more cement than OAMCS. The difference between OAMCS and AMRCS is the substitution of recycled powder and recycled coarse aggregate. The difference of carbon emission factor between Portland cement and recycled powder was as high as 751.2kg CO$_2$-eq/t. The carbon emission of recycled coarse aggregate is higher than that of natural coarse aggregate. However, in terms of carbon emissions from transport, recycled coarse aggregate is lower than natural coarse aggregate. The main reason is that there are few natural aggregate mining sites in China's urban areas, and natural aggregate must be exported from remote areas. In this study, the transportation distance of natural coarse aggregate from the place of origin to the commercial concrete plant is up to 200km, while the transportation distance of recycled coarse aggregate is not large because the demolished buildings, prefabricated component factories and project sites are all located in urban areas. Combined with production and transportation, the carbon emission of recycled coarse aggregate is lower than that of natural coarse aggregate. However, if the project is located far from urban areas and closer to natural aggregate mining sites, the opposite conclusion may be reached.

5.2. Dimension of component production
The essential difference between OAMCS/AMRCS and CCS in the production of components lies in the following: in the OAMCS/AMRCS, components are made in the factory and assembled on the site; In the CCS, building components are wholly made in the site. Therefore, it is necessary to make a comparative analysis of the component production process of the assembled integral structure and the cast-in-place structure. For the former, the calculation of carbon emissions covers the in-plant production and in-site assembly of components. For cast-in-place structures, the calculation of carbon emissions covers the processing and production of in-site components.
Table 13. Carbon emissions of component prefabrication and assembly in OAMCS/AMRCS.

| Component      | Quantity(m³) | Component prefabrication (kg CO₂-eq/m³) | Component Assembly (kg CO₂-eq/m³) | Total (t CO₂-eq/m³) |
|----------------|--------------|-----------------------------------------|-----------------------------------|---------------------|
| External wall  | 370.86       | 11.70                                   | 11.70                             | 8.68                |
| Internal wall  | 213.55       | 10.14                                   | 11.70                             | 4.66                |
| Shear wall     | 1645.62      | 14.04                                   | 12.48                             | 43.64               |
| Superposed beam| 75.54        | 9.36                                    | 9.36                              | 1.41                |
| Superposed slab| 471.22       | 9.36                                    | 9.36                              | 8.82                |
| Stairway       | 99.74        | 10.92                                   | 11.70                             | 2.26                |
| Total          | 2876.52      | -                                       | -                                 | 69.47               |

It can be seen from table 13 that the carbon emission of prefabrication and on-site assembly of each cubic meter of prefabricated member is 23.46kg. However, for the CCS, the carbon emission of the components produced on site of 3,190.53m³ is 275.51t. In other words, the carbon emission of each cubic meter of cast-in-place components is 86.35kg, which is 2.68 times more than that of the prefabricated components. The low degree of mechanization and low level of standardization and modularization of CCS construction are the main reasons for the high carbon emission of CCS component production.

5.3. Dimension of entire materialization process

From the perspective of the total materialization process, the average carbon emissions per 1m³ of components produced in CCS, OAMCS and AMRCS are 855.83kg, 633.79kg and 561.06kg, respectively. After the conversion, the average environmental cost per 1m³ of component produced in CCS, OAMCS and AMRCS is 188.28 yuan, 139.43 yuan and 123.43 yuan, respectively.

With the CCS as a benchmark, the OAMCS per 1m³ of component can save 222.04 kg of carbon emissions, which saves 48.85 yuan of the environment cost, accounting for 25.94%. On the basis of the application of recycled concrete, each cubic meter of components can further save 72.73 kg of carbon emissions, which saves 16.00 yuan of the environment cost, accounting for 8.50%.

According to the data, the newly started area of commercial housing in Chongqing in 2019 is 67.2540 million m²[14]. It is assumed that 10% of the newly started commercial housing in Chongqing in 2019 will be promoted to adopt the AMRCS instead of the traditional CCS. If the average concrete volume of each square meter of construction area is 0.35m³, the component volume of housing with a construction area of 6,725,400 m² is 2,353,900 m³, and the environmental cost that can be saved is 152,654,400 yuan. In addition, the sand and gravel industry in China also has the problem of stealing sand and gravel resources in mining mountains and rivers [15], which directly increases the supervision pressure and management expenditure of government departments. If the use of recycled products in construction are promoted, the demand for natural sand and stone can be reduced from the origin, so as to alleviate environmental and social problems caused by illegal sand and stone mining.

6. Conclusion

Based on LCA, this paper establishes a carbon emission calculation model for the whole materialization process of CCS, OAMCS and AMRCS. In order to attain a more integral model and reach more accurate analysis results, the recovery and utilization coefficient are taken into account when the carbon emissions from the production of raw materials are calculated, the no-load return coefficient is taken into account when the carbon emissions from the transportation process is calculated, and the time utilization coefficient and capacity utilization coefficient are considered when the carbon emissions from the construction of CCS machinery are calculated. Finally, the total carbon emissions in the life cycle of the three structures are calculated based on the practical cases, and the results are analyzed and discussed in three dimensions. The analysis results show that AMRCS has more significant effect on emission reduction than OAMCS and CCS, and has great promotion value.
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