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Carbon emission of recycled concrete based integrated pre-fabricated structure: case study from perspective of entire materialisation

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Abstract: To investigate the potential impact of combining pre-fabricated construction and recycled concrete on carbon emission reduction, we conducted carbon emission calculations on three types of structures: integrated pre-fabricated structures based on recycled aggregate concrete (IPSRAC), integrated pre-fabricated structures based on natural aggregate concrete (IPSNAC), and cast-in-place structures based on natural aggregate concrete (CSNAC). We used the annual average price in the carbon trading market to convert carbon emissions into enterprise costs. Our results show that IPSNAC can reduce carbon emissions by 25.9% compared to CSNAC, resulting in a cost saving of 18.2 yuan per 1 m^3 of construction components. Furthermore, IPSRAC can further reduce carbon emissions by 8.2% compared to IPSNAC, resulting in a cost saving of 5.8 yuan per 1 m^3 of construction components. Our findings provide important data for construction enterprises to make informed decisions about integrating pre-fabricated construction and recycled concrete to reduce carbon emissions.

1. Introduction

Climate change caused by global warming is a critical issue that has brought worldwide attention in recent years. In 2019, the National Oceanic and Atmospheric Administration (NOAA) declared that the global surface temperature increased by 0.95℃ compared to the 20th century average [1]. The construction industry has been identified as a significant contributor to carbon emissions, accounting for 36% of global carbon emissions [2]. As a fundamental industry in China's economy, the construction industry has a crucial mission to reduce emissions.

Pre-fabricated construction is a construction technology that produces building components in the factory in advance of on-site assembly. Jin et al. [3] studied the environmental performance of off-site facilities through the life cycle assessment (LCA) and found that the production of pre-fabricated components in the prefabrication plant has significant benefits for energy conservation and emission reduction. Du et al. [4] compared the carbon dioxide emissions of pre-fabricated components and cast-in-place structural components, and found that the carbon emissions released by pre-fabricated buildings are about 18% lower than those generated in traditional construction methods. However, most existing studies failed to take into account the recyclability of materials and compare the carbon emissions of different structures on basis of the unified computation modelling and fundamental data, which may compromise the authenticity of the reported results. On the other hand, as a basic building material, carbon emissions induced by concrete production accounted for 15% of China's total carbon emissions [5]. In this regard, the study of recycled concrete (RC), as a green alternative to conventional concrete, is vitally important. Xiao et al. [6] analysed concrete carbon emissions at different substitution ratios of recycled coarse aggregate (RCA), and reported that the transport distance and carbonation of RCA had a critical impact on reducing concrete carbon emissions. Yet, few studies considered the contribution of recycled powder (RP) towards reducing carbon emission of concrete. As a major contributor to carbon emissions in concrete, cement dominates the total carbon emission of concrete. Resultantly, the use of RP in concrete to replace part of cement is of significant benefit towards concrete production emission reduction. Thus, it is feasible to utilise RC in the integrated pre-fabricated structure [7] and further reduce carbon emissions in concrete production.

This paper establishes a comprehensive carbon emission computation model and analyses the carbon emissions of three different structures, namely CSNAC, IPSNAC, and IPSRAC. The study aims to evaluate the carbon emissions of these structures on the same modelling basis and provide insights into reducing carbon emissions in the construction industry. Furthermore, the paper converts the carbon emissions into the carbon trading price in Chongqing, which provides practical guidance for carbon emissions reduction in the construction industry.

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2. Methodology and results

2.1 Computational model

In this study, the carbon emissions released during the production process of IPSRAC, IPSNAC and CSNAC are derived using a LCA methodology spanning from cradle to grave. The main sources and differences of the carbon emissions of these three structures are analysed. 1 m^3 is selected as the functional unit. The International Energy Agency (IEA) stipulated that carbon dioxide equivalent (CO_2-eq) can be employed as a uniform unit for quantifying overall greenhouse gas emission. The computational modelling principally refers to previous studies [8-9].

2.2 Carbon emission of CSNAC

The carbon emission calculation only takes into account the processing and installation of steel bars and formwork, the production of concrete and the concrete casting of superstructures, so as to make the results of CSNAC comparable to the other two structures. The volume of main components is as follows: column 565 m^3, wall 250 m^3, beam 1285 m^3, plate 1091 m^3, a total of 3191 m^3.

Each cubic meter of C30 concrete contains 190 kg of water, 500 kg of Portland cement, 1231 kg of natural coarse aggregate (gravel, NCA) and 479 kg of natural fine aggregate (river sand, NFA). The corresponding carbon emissions are 0.2, 401.4, 30.9 and 4.5 kg. From raw material production to ready-mixed concrete completion, each cubic meter of C30 ready-mixed concrete leads to a carbon emission of 438.7 kg. The production of 3190.5 m^3 of concrete produces 1399.6 t of carbon equivalent. A total of 1026.0 t of carbon equivalent is induced by producing 653.4 t of steel bars. Hence, the carbon emission in the production phase amounts to 2425.6 t.

The mass of 1 m^3 of C30 concrete is 2360 kg, such that the mass of 3190.5 m^3 of C30 concrete equals to 7529.7 t. The carbon emission of concrete in the transport phase equals to 25.8 t. The total mass of rebar is 653.4 t, whereby the rebar's carbon emission during the transport phase corresponds to 3.7 t. Consequently, the carbon emission in the transport phase corresponds to 29.5 t.

With reference to the construction plan, we determined the quantity of working hours of construction machinery. Resultantly, the carbon emission induced by construction machinery equals to 275.5 t. In conclusion, the entire carbon emission of CSNAC during materialisation is 2730.6 t, and the carbon equivalent emission is 855.8 kg for each cubic meter of components.

2.3 Carbon emission of IPSNAC

The mix formulation of C30 concrete used for the pre-fabricated components is provided by a local pre-fabricated component plant. Every cubic meter of concrete contains 160 kg of water, 320 kg of Portland cement, 1050 kg of NCA and 800 kg of NFA. Correspondingly, their carbon emissions are 0.1, 257.1, 27.2 and 7.5 kg per kg, respectively. Every cubic meter of concrete produces 291.9 kg of carbon equivalent from the production and transportation of raw materials. Thus, from raw material production to ready-mixed concrete, the carbon emission is 292.7 kg for each cubic meter of pre-fabricated concrete.

The power supply corresponds to electricity for the streamline of the pre-fabricated construction components. The carbon emissions produced by 1 m^3 of external wall, internal wall, shear wall, sandwich beam, sandwich floorslab and stairway are 479.0, 486.3, 665.9, 631.0, 603.9 and 559.5 kg, respectively. At the same time, the carbon emissions produced by transporting 1 m^3 of external wall, internal wall, shear wall, sandwich beam, sandwich floorslab and stairway are 6.8, 6.8, 8.9, 8.4, 8.6 and 8.7 kg, respectively.

After the components arrive at the construction site, they are assembled by wheel cranes (diesel fuel consumption) and tower cranes (electric energy consumption). According to the field measuring, the carbon emissions generated via installing 1 m^3 of external wall, internal wall, shear wall, sandwich beam, sandwich floorslab and stairway are 11.7, 11.7, 12.5, 9.4, 9.4 and 11.7 kg, respectively.

The volumes of the construction components are obtained from the construction plan. The carbon emissions are 1765.3, 24.2 and 33.7 t for production, transportation and on-site construction, respectively. Consequently, the overall carbon emission of IPSNAC during materialisation is 1823.2 t, and the carbon equivalent emission is 633.8 kg for each cubic meter of construction components.

2.4 Carbon emission of IPSRAC

On the basis of an IPSNAC engineering example, RCA and RP can be adopted as an alternative of 50% of NCA and 30% of Portland cement, respectively, in IPSRAC concrete. As a result, each cubic meter of concrete comprises 175 kg of water, 233 kg of cement, 100 kg of RP, 540 kg of RCA, 540 kg of NCA, 770 kg of NFA, corresponding carbon equivalents of 0.2, 187.2, 4.6, 5.2, 14.0 and 7.2 kg. The total equivalent carbon triggered by the production and transportation of raw materials is 218.3 kg per cubic meter of RC. Also, the carbon emission of concrete mixing is configured as 0.7 kg CO_2-eq/m^3. Thus, the carbon emission is 219 kg for each cubic meter of RC, considering the entire materialisation (i.e. from the production of raw material to the completion of concrete mixing).

The application of RCA and RP is able to prevent wasted concrete from being transported to and being buried in landfilling sites. The carbon emissions averted ought to be considered in the production and transportation of RCA and RP, reflecting the contribution of recycled products to carbon emission reduction. The carbon emission factor of RCA production corresponds to 6.7 kg CO_2-eq/t, whilst that of RP production corresponds to 42.7 kg CO_2-eq/t. After deducting the avoided carbon emission of wasted concrete, the carbon emission factor of the RCA and RP corresponds to 17.1 kg CO_2/10 t.

The technical pathway, category, quantity and material composition (except for concrete) in IPSRAC components are the same as those in IPSNAC ones. For every cubic meter of external wall, internal wall, shear wall, sandwich beam, sandwich floorslab and stairway, the carbon emissions are 421.5, 428.9, 592.2, 557.3, 530.2, and 485.8 kg, respectively. Since the density of RC, basically, is the same as that of natural aggregate concrete (NAC), the carbon emission of IPSRAC during transportation is considered the same as that of IPSNAC. Moreover, as the number of components and the mode of component installation in IPSRAC are the same as those in IPSNAC, the carbon emissions in IPSRAC are the same as those in IPSNAC in the on-site construction phase.

The carbon emissions amount to 1562.9, 24.2, and 33.7 t, respectively, for production, transportation and on-site construction. Hence, the total carbon emission in IPSRAC in the entire materialisation is 1620.7 t, and the carbon equivalent emission is 563.4 kg per cubic meter of components.

3. Discussion

As far as all the three structures are concerned, the carbon emissions in the production phase account for the largest proportions in the entire materialisation. In the production phase, the difference in material compositions are found to be the most critical factor leading to the difference in the carbon emissions in the three structures. In addition, by comparing CSNAC to IPSNAC/IPSRAC, the differences in manufacturing techniques of building components are found as an inducement to large differences in their carbon emissions.

Every 1 m^3 of CSNAC components contains 204.8 kg of rebar, whilst every 1 m^3 of IPSNAC/IPSRAC components contains 179.3 kg of rebar. The different external conditions caused by different project locations are believed to be the major reason for the distinction in the steel content. Additionally, CSNAC completed its component production on site, so that more difficulties (e.g. low-level mechanisation) could be found in guaranteeing the quality of construction components. By contrast, the IPSNAC/IPSRAC components are prepared by the pre-fabricated component manufacturer, which conduces to the component quality. Consequently, the structural design engineering may reduce the safety factor properly, signifying a reduced steel content. On the other side, CSNAC adopts concrete pumps to transport concrete, in which way an increased quantity of cement is needed to lubricate the pipe wall during pumping. This reason behind is the quantity of cement significantly impacts the pumping efficiency by varying the pipe-wall friction and the degree of filling in the pump pipe. The remarkably increased amounts of rebar and cement rationalise the much greater carbon emission of CSNAC.

The difference between IPSNAC and IPSRAC lies in the replacement of RP and RCA. The carbon emission factor of Portland cement is 751.2 kg CO_2-eq/t higher than that of RP. In terms of aggregate production alone, the carbon emission of RCA (6.7 kg CO_2/t) is greater than that of NCA (3.1 kg CO_2/t). However, RCA (54.6 kg CO_2/10 t, i.e. from demolished buildings to construction sites) is lower than NCA (157.0 kg CO_2/10 t, i.e. from the raw material site to the construction site) in terms of carbon emissions induced by transportation. The main reason is that there are almost no natural aggregate (NA) mining sites in urban areas in China, and NA has to be exported from remote areas. In this study, the transportation distance of NCA between the origin to the concrete mixing plant is assumed to be 200 km. However, since demolished buildings, pre-fabricated components factories and construction sites are situated in urban areas, the transportation distance of RCA can be reduced. From the perspective of production and transportation, the carbon emission of RCA is lower than that of NCA. Nonetheless, on condition that the construction site is situated far away from urban areas and closer to NA mining sites, the opposite conclusion may be obtained.

This study calculated the carbon trading price from May 1, 2019 to April 30, 2020 in Chongqing, whereby the average price of 81.9 yuan/ton is obtained. Therewith, carbon emissions produced by 1 m^3 of concrete of the three structures can be converted into a carbon emission trading cost, as shown in Figure 1. The carbon emissions of CSNAC, IPSNAC and IPSRAC are 438.7, 292.6 and 219.0 kg/m^3 respectively, and the corresponding carbon trading costs are 35.9, 24.0 and 17.9 yuan. Therefore, taking CSNAC concrete as the benchmark, every cubic meter of IPSNAC concrete saves 12.0 yuan of carbon trading cost. On this basis, if RC is put into practice, carbon trading cost can be further reduced by 6.0 yuan.

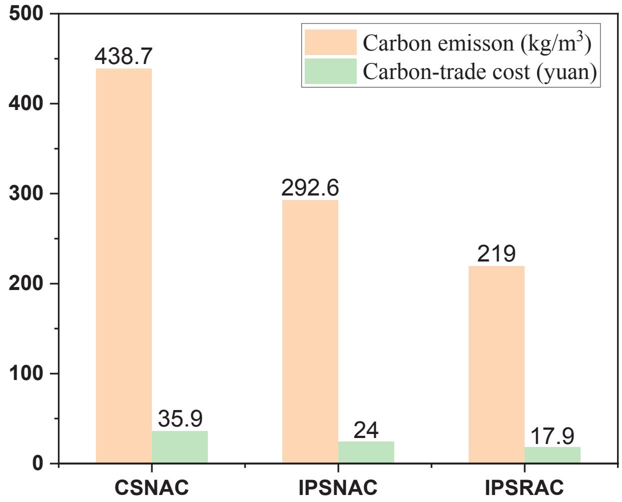

Figure 1 Carbon emission and carbon-trade cost for concrete production

The intrinsic difference between IPSNAC/IPSRAC and CSNAC component production consists in the fact that the IPSNAC/IPSRAC components are well prepared in the pre-fabrication factory and subjected to assembling on construction site while the CSNAC components are fully manufactured on site.

For IPSNAC/IPSRAC, the carbon emission accounting covers the component production in factory and the component assembling on site. In the case of CSNAC, the carbon emission accounting covers the processing and fabrication of components on site. The carbon emission triggered by the pre-fabrication and on-site assembling is 23.5 kg for 1 m^3 of components. By contrast, the carbon emission is 86.4 kg per 1 m^3 of cast-in-place components, which is 3.7 times as much as that of the pre-fabricated component. The low streamlining and mechanisation degree of CSNAC construction and the low standardisation and modularisation level may rationalise the sizable carbon emission of the CSNAC component manufacturing.

In a similar way, the carbon emissions during the entire materialisation of cubic meter of the components of the three structures can be converted into carbon trading costs, as shown in Figure 2. The carbon emissions of CSNAC, IPSNAC and IPSRAC are 855.8, 633.8 and 563.4 kg/m^3, respectively, and the carbon trading costs are 70.1, 51.9 and 46.2 yuan accordingly. Based on CSNAC, IPSNAC can save 18.2 yuan of carbon trading costs per 1 m^3 of components. On this basis, if the RC is applied, the carbon trading cost of 1 m^3 of components can be further decreased by 5.8 yuan.

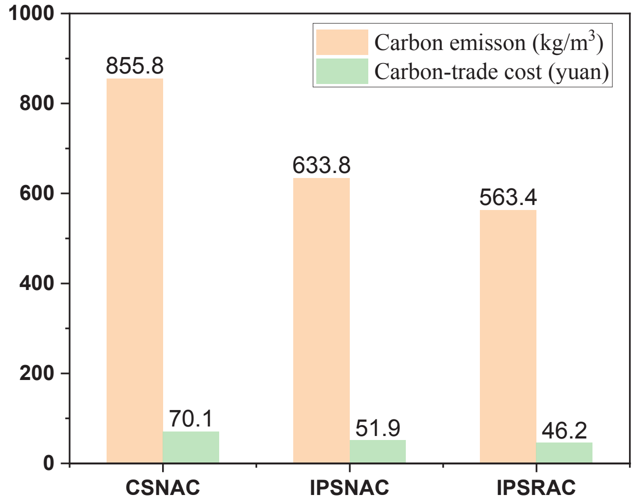

Figure 2 Carbon emission and carbon-trading cost during entire materialization

In 2019, Chongqing newly developed a commercial housing area of 67.254,000 m^2. This study assumes that IPSRAC is used to replace CSNAC in 10% of the newly developed area. As the concrete volume of every 1 m^2 of housing area is assumed to be 0.35 m^3 on average, 56.376,000 yuan of carbon trading cost can be saved. In addition, there have been a problem of illegal mining in Chinese industry of sand and stone exploitation for long [10], posing a great pressure and cost of administration for governmental agencies. If the application of recycled products in housing can be subjected to popularisation, the demand for natural aggregate resources (e.g. river sand, cobble and gravel) can be retrenched at root, thus alleviating environmental and social burden caused by illegal mining.

4. Conclusions

The paper presents the results of the carbon emission accounting model based on LCA theory for the entire materialization of CSNAC, IPSNAC, and IPSRAC structures. The study conducted case studies to calculate the overall carbon emissions for each of these structures. The results of the study show that IPSRAC has the lowest carbon emissions compared to IPSNAC and CSNAC. Specifically, the study found that IPSNAC reduces 25.9% of carbon emissions per 1 m^3 of construction components compared to CSNAC. This reduction corresponds to approximately 18.2 yuan of carbon-trade costs. Furthermore, IPSRAC reduces carbon emissions by an additional 8.22% per 1 m^3 of construction components compared to IPSNAC. This reduction corresponds to approximately 5.8 yuan of carbon trading costs. The findings of the study suggest that IPSRAC is the most environmentally friendly construction method among the three structures studied. The study also provides valuable insights into the carbon trading costs associated with each structure, which can help stakeholders in the construction industry make informed decisions regarding construction methods and carbon emissions reduction. In conclusion, the paper's results highlight the critical importance of using LCA-based carbon emission accounting models for entire materialization in the construction industry. The study provides valuable insights into the carbon emissions of different construction methods and their associated carbon trading costs. These insights can help policymakers and stakeholders in the construction industry make informed decisions to reduce carbon emissions and promote sustainable development.

References

1. Li J., Liu Y. (2015) Carbon emission accounting model based on building lifecycle. Journal of Engineering Management, 29(4):12-16. 10.13991/j.cnki.jem.2015.04.003
2. Ma X.M., Cai Y. (2014) China Low-carbon Finance Development Report. Peking University Press, Beijing. https://bbs.pinggu.org/thread-5063717-1-1.html
3. Jin R.Y., Hong J.K. and Zuo J. (2019) Environmental performance of off-site constructed facilities: A critical review. Energy and Buildings, 207: 109567. 10.1016/j.enbuild.2019.109567
4. Du Q., Bao T., Li Y., Huang Y.D. and Shao L. (2019) Impact of prefabrication technology on the cradle-to-site CO_2 emissions of residential buildings. Clean Technologies and Environmental Policy, 21: 1499-1514. https://doi.org/10.1007/s10098-019-01723-y
5. China Energy and Carbon Emissions Research Group 2050. (2010) China Energy and Carbon Emissions Report 2050. Science Press, Beijing. https://thinktank.sciencereading.cn/booklib/v/bookPreview/122/246/1321882.html
6. Xiao J.Z., Li A. and Ding T. (2016) Lifecycle CO_2 emission evaluation of recycled concrete. Journal of Southeast University (Natural Science Edition), 46 (5): 1088-1092. https://scsc.tongji.edu.cn/_upload/article/files/cb/f9/8683b5304f54bb2017a68b502b38/1211b3b9-40c2-4d85-88cb-090babec8e9b.pdf
7. Shi J.G. (2012) Engineering Application and development approach of Recycled Concrete. In: the Third National Recycled Concrete Academic Exchange Conference. Qingdao. pp. 23-29. https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CPFD&dbname=CPFD0914&filename=OGTY201209002007&uniplatform=NZKPT&v=7F9R1KmRDxpVhsVg9mCHzgTJoib1PJfzlsxpfzLqAP3sNkUAFt-UyqaQn-I5QbS82Br8Gm6E8wo%3d
8. Tinoco M.P., Mendonca E.M., Fernandez L.I.C., Caldas L.R., Reales O.A.M. and Filho R.D.T. (2022) Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review. Journal of building engineering, 52: 104456. https://doi.org/10.1016/j.jobe.2022.104456
9. Ma S. (2020) Carbon emission modelling and analysis. IOP Conference Series: Earth and Environmental Science, 531: 012049. doi: https://doi.org/10.1219/j.esr.2022.101021
10. Wang J.J., Lang Y. (2018) Research on the development status and countermeasures of sand and stone industry in our country under new situation. Building Materials Development Guidance, 16(08): 3-8. https://xueshu.baidu.com/usercenter/paper/show?paperid=3d495f4a47dc3c4546f062593af7ff7b