Contributions of C&D Waste Recycling to Carbon Reduction in the Construction Industry, a City-Scale Study in Japan

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建設産業における二酸化炭素の排出削減では工事に使うコンクリートや鋼材のリサイクル・リユースによって廃棄物を減らす努力が重要になる。本稿では北九州市の取り組みを検証し、建設資材循環利用の可能性を探った。

Abstract

The construction sector accounts for 30% of Japan's carbon emissions. To achieve carbon neutrality by 2050, the construction sector is an important key sector with significant potential. Compared with other stages of building life cycle, there is still a research gap on the carbon emission in demolition stage, especially the disposal of the construction and demolition waste (C&D waste). This study introduces the concept of "circular economy" and uses process-based life cycle assessment (LCA) methods to evaluate the environmental impact of C&D waste in a Japanese city and examines the carbon reduction benefits of re-resource the waste. The findings include (1) In 2019, the city generated about 1.28 million tons of C&D waste with a recycling rate of more than 95%. (2) Concrete and metal recycling is a major source of carbon emissions, highlighting the need for improved recycling technologies. (3) The carbon emissions of waste disposal and the carbon benefits of using recycled materials are more than balanced, nearly 10 thousand tons of CO_2 are reduced. This study shows the enormous potential for negotiation and auction of C&D waste. The results provide implications for optimizing waste management and provide a model for strengthening recycling efforts, thereby supporting sustainable development.

Keywords construction industry, carbon emissions, C&D waste recycle, process-based LCA

1. Introduction

The construction industry is a major consumer of energy, responsible for nearly 40% of global carbon emissions[1], significantly contributing to environmental challenges such as climate change. As a key sector in achieving the Sustainable Development Goals (SDGs), its carbon emissions have garnered widespread attention. The design of low-carbon buildings and the pursuit of sustainable development within the industry have become critical areas of research.

Currently, most studies on carbon emissions in the construction industry focus on reducing emissions during the operational phase of buildings, emphasizing the built environment and energy efficiency in operation as core elements of design. However, as a resource-intensive sector, the construction industry uses substantial quantities of high-carbon materials during the construction phase, making "material carbon" a significant contributor to overall emissions[2]. This highlights the considerable potential for carbon reduction in material use, which has not yet received sufficient attention within the industry.

This study introduces the concept of a "circular economy" to the construction industry, shifting away from the traditional linear model of "construction–operation–demolition" and instead viewing buildings as part of a closed-loop system, as shown in Fig.1.

The focus of this paper is on the demolition phase, where large volumes of waste are generated. This waste is regarded as a valuable resource, to be recycled and

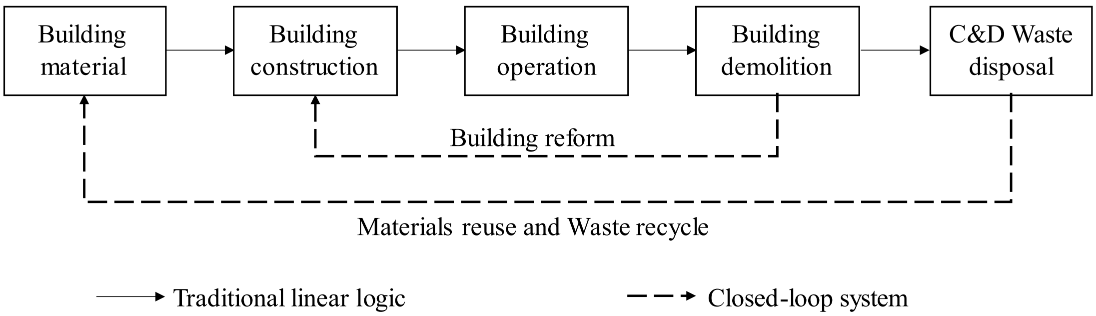

Fig. 1. Closed-loop system in construction sector

reintegrated into the building life cycle as recycled materials. Carbon emissions from the waste generation and recycling processes will be accounted for and attributed to the demolition phase, addressing the gap in carbon emission research within the industry. The carbon emissions of recycled materials will be compared with those of new materials, demonstrating the carbon reduction potential of using recycled resources.

In Japan, a developed country, the construction industry has entered an inventory phase, where building abandonment and vacancy have become pressing social issues. The demolition of these abandoned buildings, along with frequent updates to building stock, results in large volumes of construction and demolition waste (C&D waste). These challenges are particularly evident in certain Japanese cities with some of the oldest and most rapidly aging populations.

This paper identifies the selected city as representative of broader trends, making it the focus of this research. The study aims to clarify the processes involved in the disposal of C&D waste, estimating carbon emissions across four key stages: demolition, transportation, intermediate treatment and final disposal. By accounting for carbon emissions, the research assesses the carbon reduction potential of using recycled materials. The findings of this study will not only help optimize C&D waste management in the city but also provide a valuable reference for other cities looking to develop waste recycling industries, ultimately contributing to sustainable development.

2. Methodology

2.1 Research scope

This study focuses on the environmental impact of building demolition and the subsequent waste disposal processes. In the background of global warming, CO_2 emissions are used as the primary indicator to evaluate environmental impacts. Fig. 2 outlines the research framework, with a process-based life cycle assessment serving as the main evaluation tool. According to the accounting methodology, the carbon emissions from the whole life cycle of C&D waste are divided into four stages: the generation, transportation, treatment, and final landfill.

It is important to note that although C&D waste originates from both building construction and demolition, this study only accounts for the carbon emissions from the demolition phase. The rationale is that waste generated during construction is a by-product of the creation of new buildings, representing material wastage. Therefore, its carbon emissions should be attributed to the construction phase, not the demolition phase.

In 2019, Japan's Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) conducted a detailed survey on C&D waste[3], providing comprehensive data on waste disposal processes, transportation distances, and other related information. For this reason, 2019 was selected as the reference year for this study.

Based on Japan's policies and regulations governing the construction industry and waste recycling[4], this research focuses on 10 typical types of C&D waste, along with mixed waste that is difficult to further classify, as presented in Table 1.

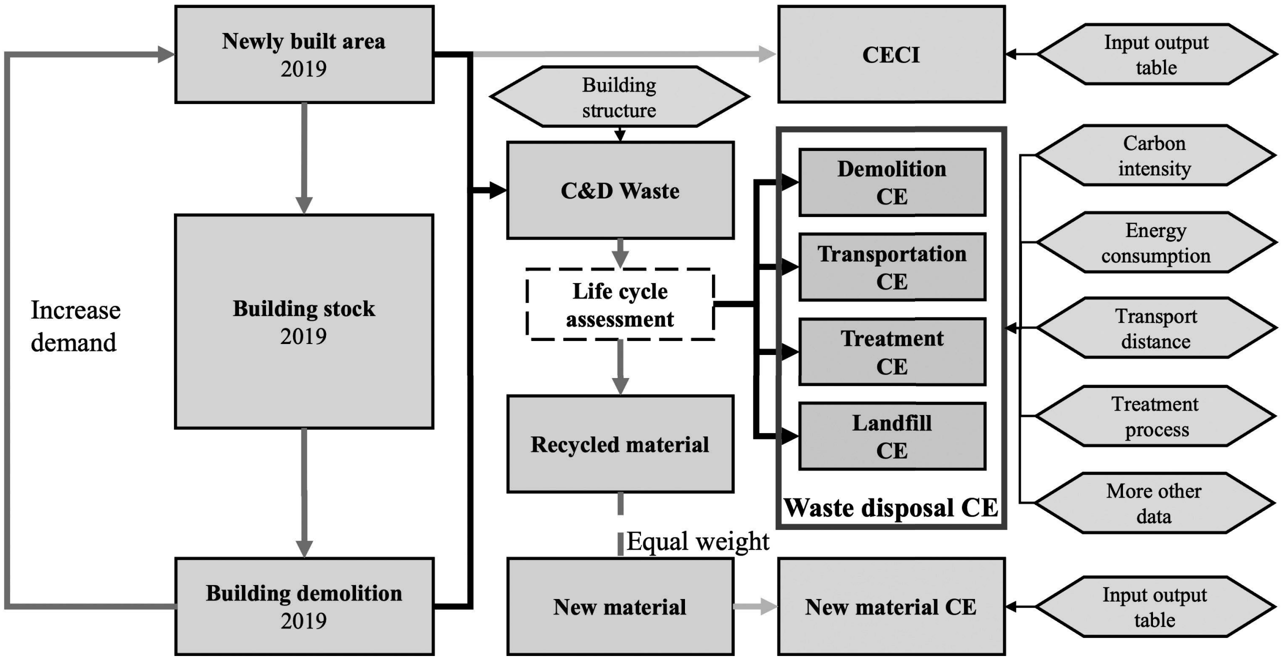

Fig. 2. The research framework

Table 1. Products of main C&D wastes

C&D waste	Re-resource way	Recycling products	New products
Asphalt concrete	Recycle	Aggregate and Asphalt concrete	Gravel and asphalt & gravel
Concrete block	Recycle	Aggregate	Gravel
Construction wood &	Reuse	Beams or columns	Sawed timber
logging wood	Recycle	Wood chips	Wood chips
Waste plastics	Recycle	Plastic pellets	Plastic pellets
	Regenerate	Styrene monomer	Thermoplastic Resins
Wastepaper	Recycle	Paper pulp	Paper pulp
Metal scrap	Recycle	Crude steel	Crude steel
	Reuse	-	Construction metal products
Waste plasterboard	Recycle	Gypsum powder	Gypsum
Construction Soil	Reuse	-	-
Sludge	Reuse	Backfill soil	-

2.2 Waste and re-resource products

The process of re-resourcing C&D waste is simplified in Fig.3. Re-resourcing waste is often further subdivided into three categories: reuse, recycle, and regenerate[5]. The main differences between these categories lie in the treatment processes and the state of the products after treatment. Reuse involves treating dismantled materials in a simple manner and then using them directly without altering their shape or characteristics. Recycle refers to collecting, separating and reprocessing demolition materials into constituent construction materials. Regenerate entails collecting, separating and completely decomposing demolished materials into raw materials.

Depending on the intended reuse, C&D waste undergoes various intermediate treatment processes, allowing a single type of waste to be transformed into different recycled materials or building components. Table 1

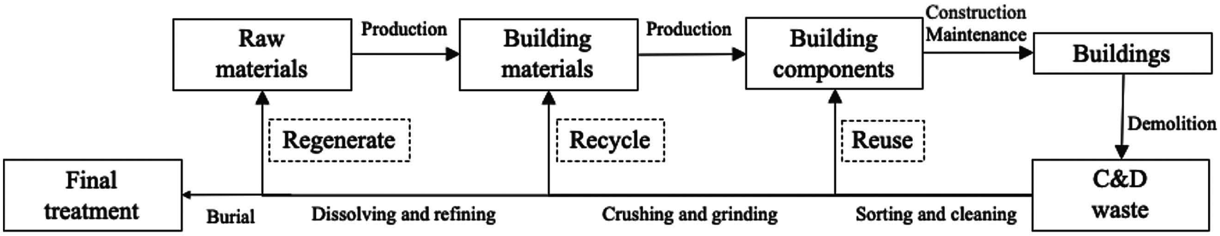

Fig. 3. Recycling of building materials

provides an overview of the primary C&D wastes and their corresponding recycled products using current technologies, while also identifying the closest matching products to facilitate comparisons of carbon reduction benefits.

For instance, waste concrete blocks are crushed and used as aggregates for concrete. Around 33.3% of asphalt concrete is recycled as aggregates, with the remainder recycled as asphalt composite. It is assumed that the ratio of asphalt to other stones in the composite is 3.8:100. Waste wood is typically crushed into wood chips, while compressed and crushed wastepaper is mixed with water to be recycled into pulp. Waste plasterboard is recycled into gypsum powder through sorting and grinding, and metal fragments are melted to produce crude steel.

Plastics are divided into thermoplastics and thermosets, with each processed according to its nature. Thermoplastic plastics, such as PVC pipes and Styrofoam, can be melted and reprocessed after crushing, while thermosetting plastics require chemical dissolution for reprocessing or are crushed to serve as auxiliary materials. In this paper, the re-resourcing method for plastics in C&D waste is defined as recycle, with the intermediate treatment involving the grinding of plastic waste into granules, due to the high proportion of thermoplastics. Thermosetting plastics also follow a recycling path as crushed materials for road construction.

Sludge is typically treated and used as backfill along with construction soil, classified under reuse. Additionally, some wooden components can be reused directly after simple cleaning.

Recycling is the most common method of re-resourcing C&D waste. After treatment, C&D wastes generally become recycled building materials that enter the manufacturing process as substitutes for new materials. Since the process of recycling construction materials is the same as manufacturing construction components from new materials, the intermediate treatment process in this paper refers to the production of construction materials from C&D waste through recycling. The environmental benefits assessed in this study refer to the difference in carbon emissions between recycled materials and their corresponding new materials.

2.3 Waste estimation and its flow

The amount of C&D waste generated depends on the types and quantities of building materials used during the construction process[6], which are closely related to the building's structural design. This implies that the waste produced during the demolition of buildings with different structures will vary significantly, necessitating separate calculations based on building structure. Additionally, C&D waste arises from different phases for distinct reasons and must be calculated independently. For example, as shown in Formula (1), the total amount of C&D waste generated equals the sum of waste from the demolition process and the waste generated from the construction of new buildings across all structural types.

Due to the difficulty of obtaining detailed waste data for each demolished building, the unit area intensity method is often employed to estimate C&D waste[7]. Formula (2) can be used to calculate the waste generated during the demolition of buildings with various structures, and the waste generated during new construction can be estimated in a similar manner.

$$\boldsymbol{W_{Total}}=\sum_1^i \boldsymbol{W_D^i} + \sum_1^i \boldsymbol{W_C^i} \quad (1)$$

$$W_D^i = \sum_1^i A_D^i \cdot WI_D^{i,j} \quad (2)$$

Where, $\boldsymbol{W_{Total}}$ means the total of C&D waste generation, $\boldsymbol{i}$ means different building structures, $\boldsymbol{W_D^i}$ means waste generation from the demolition of i structure buildings, $\boldsymbol{W_C^i}$ means waste generation from the construction & renovation of i structure buildings, $\boldsymbol{A_D^i}$ means demolition area of i structure buildings, $\boldsymbol{WI_D^{i,j}}$ means waste generation intensity of waste j of i structure buildings (tons/m2).

Once C&D waste is generated, the disposal process begins. The waste survey conducted by MLIT provides detailed records of this process, which are summarized in Table 2.

2.4 Carbon emission assessment

The carbon emission assessment is carried out using the IPCC methodology. The total carbon emissions from waste disposal are calculated by summing the emissions from the four stages of the whole life cycle of C&D waste, as shown in Formula (3).

$$CE=\sum_1^k CE^k \quad (3)$$

Where, $\boldsymbol{CE}$ means the total carbon emission from the C&D waste disposal, $\boldsymbol{k} = \mathbf{4}$, means the four stage, generation, transport, intermediate treatment and final disposal.

The carbon emissions from the C&D waste generation process is the carbon emissions from building demolition, which comes from the energy consumption of the demolition process. In this study, a survey of construction and demolition companies in the city was conducted to account for their energy consumption. Diesel fuel is the main source of energy for demolition activities and is used to drive cranes, bulldozers, crushers and other machinery on site. Electricity is used for on-site lighting and to drive small demolition equipment, while kerosene and gasoline account for a relatively small share and are mainly used for on-site power generation. In summary, the carbon emissions of the demolition phase can be calculated using formula (4), and each energy consumption can be estimated by the energy required to demolish a unit area, as in formula (5).

$$\boldsymbol{CE^{dem}}=\sum_1^q \boldsymbol{Q^q \cdot EF^q + Q^{Ele} \cdot CI^{Ele}} \quad (4)$$

$$\boldsymbol{Q^q = QI^q \cdot A_D} \quad (5)$$

Where, $\boldsymbol{CE^{dem}}$ means the carbon emission from the building demolition, $\boldsymbol{q}$ means the different energy sources, $\boldsymbol{Q^q}$ means the consumption of energy q, $\boldsymbol{EF^q}$ means the emission factor of energy q, $\boldsymbol{Q^{Ele}}$ means electricity consumption from the grid, $\boldsymbol{CI^{Ele}}$ means carbon intensity of electricity, data from power companies, and $\boldsymbol{QI^q}$ means the energy q demand to demolish per unit area, obtained by investigation.

The carbon emissions generated during transportation

Table 2. C&D waste flow (%)

C&D waste	On-site disposal	Transport	Intermediate treatment	Final				
				Recycle	Reuse	Capacity reduction	Landfill	Burn
Asphalt concrete	2.9	97.1	94.8	94.8	0.8	0.0	1.6	0.0
Concrete block	5.4	94.6	94.0	94.0	0.3	0.0	0.3	0.0
Mixed waste	0	100.	76.0	60.3	0.0	0.9	34.8	4.1
Construction wood	5.8	94.2	91.2	91.0	0.5	0.1	1.8	0.8
Logging wood	4.2	95.8	87.5	87.4	5.3	0.2	0.5	2.4
Waste plastics	0	100	99.5	53.4	0.0	20.4	26.3	0.0
Wastepaper	13.8	86.2	86.2	60.9	0	16.0	9.4	0
Metal scraps	0	100	99.1	99.1	0.9	0.0	0.0	0
Waste plasterboard	0	100	100.0	87.5	0.0	0.0	12.5	0
Construction Soil	16.9	83.1	-	-	77.2	-	5.9	0
Sludge	2.0	98	95.9	91.4	0.1	3.7	2.7	0

result from the fossil fuel consumption of transport vehicles, as represented by Equation (6). In this study, the transport vehicles are assumed to be 10-ton capacity trucks with a fuel consumption rate of 0.3 liters of diesel per kilometer.

$$CE^{tran} = \sum_{1}^{j} \frac{W_{tran}^{j} \cdot L^{j} \cdot F_{avg} \cdot EF^{diesel}}{c \cdot \eta} \quad (6)$$

Where, $\boldsymbol{CE^{tran}}$ means the carbon emission from the waste transportation, $\boldsymbol{L^{i}}$ means the transport distance of each transport for waste i, $\boldsymbol{F_{avg}}$ means the unit fuel consumption, $\boldsymbol{EF^{diesel}}$ means the emission factor of energy diesel fuel, C means the capacity of truck, $\boldsymbol{\eta}$ means the full load rate of the truck.

Intermediate treatment is a highly complex operation that involves equipment such as crushers, blowers, and compressors. The energy consumed by this equipment is the primary source of carbon emissions. Ogawa conducted a survey of 15 intermediate treatment companies to collect data on the processing capacity and energy consumption of the machinery used[5]. This study draws on Ogawa's data to estimate carbon emissions, which can be calculated using Formula (7).

$$CE_{inter} = \sum_{1}^{j} \sum_{1}^{q} W_{inter}^{j} \cdot QI_{inter}^{j,q} \cdot EF^{q} \quad (7)$$

Where, $\boldsymbol{W_{inter}^{j}}$ means the weight of intermediate treatment waste j, $\mathbf{QI}_{\boldsymbol{inter}}^{\boldsymbol{j,q}}$ means intensity of energy q consumption during waste i disposal.

At the final disposal stage, a portion of the waste is incinerated for power generation, while landfills are typically used for the disposal of materials such as concrete blocks and mixed waste. In this study, waste incinerated for power generation is considered as exiting the building cycle, and its carbon emissions are attributed to the power generation industry. Therefore, only the carbon emissions from landfilling are considered, as shown in Formula (8).

$$CE_{final} = \sum W_{landfill} \cdot EI_{landfill} \cdot E \cdot EF^{diesel} \quad (8)$$

Where $W_{landfill}$ means the landfill weight of waste, $EI_{landfill}$ means the intensity of energy consumption, E means the work efficiency of landfill.

To assess the carbon reduction benefits of C&D waste re-resourcing, this study employs the IPCC method to calculate the direct carbon emissions from the production of new materials. Additionally, the input-output method is used to estimate indirect carbon emissions. Japan's industry classification is highly detailed, with over 400 sectors. Input-output tables capture the interrelationships between economic activities and material flows, enabling the analysis of the connections between economic activity, energy consumption, and CO_2 emissions, as well as the assessment of environmental impacts. The direct and indirect carbon emissions of the materials sector are referenced from Zhao's research[8]. The relationship between the carbon emissions of new materials and their respective sectors is outlined in Formula (9).

$$CE_{new}^{a} = M^{a} \cdot (CE_{sector}) / M_{sector} \quad (9)$$

Where, $\boldsymbol{CE_{new}^{a}}$ means carbon emissions from material a, $\boldsymbol{M^{a}}$ means weight of material a, $\boldsymbol{CE_{sector}}$ means the total carbon emission from sector, $\boldsymbol{M_{sector}}$ means total weight of products in sector m.

3. Result

3.1 Life Cycle of C&D Wastes

This study estimates the generation of C&D waste in study city in 2019, as shown in Fig. 4. Over 70% of the approximately 1,276 kilotons of C&D waste come from demolition activities, making demolition the primary source of waste.

Due to the differing nature of various waste types, the sources vary significantly. Construction soil is mainly produced during new construction or renovation and far exceeds that from demolition. This is because topsoil must be replaced and the site leveled during new construction, generating a large amount of construction soil. In contrast, the concrete block waste comes from the demolition stage, accounting for over 96%. Concrete blocks, as a core material in modern construction, are not only widely used but also the largest source of C&D waste, with a total of 7.35 million tons, comprising 57.6% of total waste.

Paper waste has a unique source profile, with similar output from both the demolition and new construction stages. Paper products are commonly used as decorative materials in existing buildings and as packaging for transporting new materials, contributing to paper waste at both stages. However, the total output is relatively low, at around 1 kiloton.

Construction wood waste primarily comes from wooden buildings, totaling more than 64.5 thousand tons, which reflects the widespread presence of wooden structures in Japan. Logging wood refers to trees and shrubs cleared from construction sites, though its output is much lower than that of construction wood. In addition, metal waste (14.9 kilotons), plastic waste (6.1 kilotons), and nearly 10 thousand tons of mixed waste further highlight the diversity and complexity of C&D waste. The study shows that demolition activities generate large amounts of material waste, while the construction and renovation phases primarily produce waste related to earthmoving and site preparation.

This study also analyzes the treatment processes for C&D waste, including on-site disposal, reuse, recycling, volume reduction, landfill, and incineration. Different waste types are treated in distinct ways, as shown in Fig. 5.

Construction soil and concrete blocks are the two main types of waste. Construction soil is mainly managed through on-site disposal and reuse, often used for land formation either on-site or transferred to other locations, with these methods accounting for more than 94% of total construction soil. Concrete blocks have the highest recovery rate, with approximately 677.7 kilotons recycled, 38.7 kilotons disposed of on-site, and a small amount sent to landfill. This suggests that construction soil is predominantly reused or disposed of on-site, while concrete blocks are largely recycled.

Asphalt concrete and mixed waste undergo various treatments. Asphalt concretes are mostly recycled, with about 39.2 thousand tons processed. Approximately 5.6 thousand tons of mixed waste is recycled, though a larger portion is landfilled, and 0.4 thousand tons is incinerated. While both types of waste are partially recycled, mixed waste sees a higher proportion going to landfill and incineration.

Construction wood and logging wood also have high recycling rates. About 60.3 kilotons of construction wood and 5.4 kilotons of logging wood are recycled. These two types of waste are also subject to on-site disposal, reuse, and landfill, highlighting the important role of wood in C&D waste management.

Plastic and paper waste are mainly handled through recycling and landfilling. Of the waste plastic, 3.3 kilotons are recycled, while 1.6 kilotons are landfilled. For paper waste, 0.7 kilotons are recycled, with the remainder subjected to volume reduction or landfill. This indicates that while both types of waste have some recycling potential, landfill remains a significant disposal method.

Finally, metal waste and plasterboard waste are almost entirely recycled. Metal waste sees 14.8 kilotons recycled, and 8.6 kilotons of plasterboard waste is also recycled, demonstrating the strong recyclability of these materials with minimal landfill.

Overall, recycling is the predominant treatment method for most C&D waste, especially for concrete blocks, metal scrap, and wood. On the other hand, construction soil is more reliant on on-site disposal and reuse.

3.2 Environmental impact

3.2.1 Carbon emissions from demolition

According to Formulas (4) and (5), the carbon emissions from the building demolition process are estimated based on the amount of C&D waste generated. Given the prevalence of wood-framed buildings in the city, this paper analyzes these separately, as shown in Fig. 6. In 2019, the total carbon emissions from building demolition were estimated at 9.9 kilotons. Of this, 2.6 kilotons of CO_2 were emitted from the demolition of wood-framed buildings, while 7.3 kilotons were emitted from the demolition of other building types.

There are notable differences in the carbon emission contributions of various wastes during the demolition of wood-framed versus other types of buildings. For timber constructions, the main sources of carbon emissions were building wood (0.6 kilotons), concrete blocks (1.7 kilotons), and metal scrap (60.6 tons). In contrast, for other buildings, concrete blocks had the highest carbon footprint (6.2 kilotons), followed by construction soil (0.3 kilotons) and metal waste (93.7 tons).

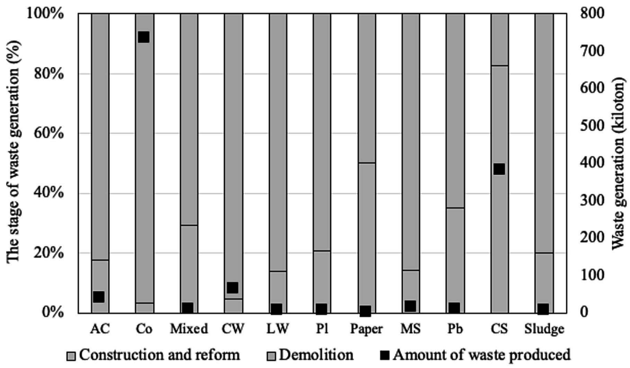

Fig. 4. The C&D waste generation of 2019

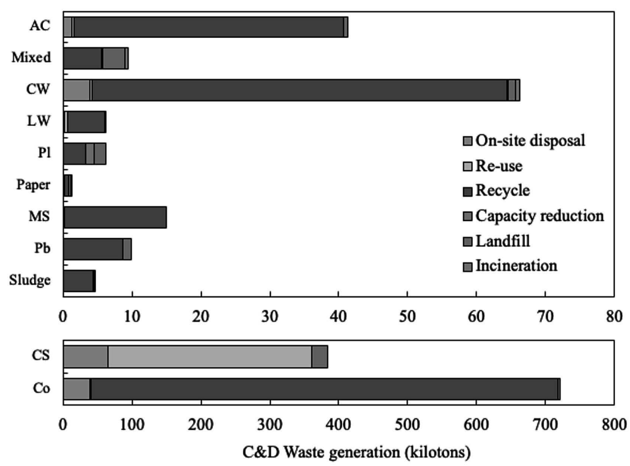

Fig. 5. The treatment flow of C&D waste

Due to simpler demolition processes, and lower fuel consumption, the carbon emission intensity for wood-framed buildings is lower, at 8.2 $kgCO_2/m^2$. In contrast, other buildings, which use large amounts of concrete and metal materials and have higher structural strength, are more difficult to demolish. This requires more demolition equipment and energy, leading to higher carbon emissions, at 14.92 $kgCO_2/m^2$.

Overall, concrete blocks and wood are the primary sources of carbon emissions during building demolition, especially in non-wooden buildings where the extensive use of concrete contributes to the highest emissions. These findings indicate that optimizing the treatment of concrete and wood waste will be key to effectively reducing carbon emissions in future construction waste management and carbon reduction strategies.

3.2.2 Carbon emissions from transportation

Fig.6 shows the carbon emissions from the transportation of C&D waste, estimated using transportation data and Formula (6). In 2019, a total of 1.2 kilotons of CO_2 were emitted from the waste transportation. Concrete blocks, construction soil, and construction wood were the main contributors, accounting for 43.3%, 35.3%, and 9.4% of total emissions, respectively. The city's well-developed recycling industry ensures that C&D waste is transported over similar distances, so transportation carbon emissions are primarily influenced by the volume of waste generated.

As shown in Fig.7, the carbon emission factor for transporting each type of waste was calculated. The highest carbon emission factor was for the transportation of waste gypsum and waste plastic, at 3.9 $kgCO_2$/ton, while the lowest was for the transportation of concrete blocks, at 1.2 $kgCO_2$/ton. The average carbon emission factor for transporting C&D waste in the city is 1.6 $kgCO_2$/ton, which is lower than in other studies[9]. Due to the city's well-developed recycling industry, the waste transportation distances are much shorter than in other cities. The localization of the recycling industry, supported by relevant policies, effectively reduces transportation distances and thus lowers carbon emissions.

3.2.3 Carbon emissions from intermediate treatment

Fig. 8 highlighting the emission characteristics of each type. Metal and concrete blocks are the primary contributors to carbon emissions. Although the total amount of metal waste is only 14.8 kilotons, it generates the highest carbon emissions, amounting to 12.9 kilotons. Concrete blocks, with a much larger waste volume of 677.7 kilotons, correspond to carbon emissions of 9.7 kilotons. The next largest contributor is asphalt concrete waste, which produces 0.6 kilotons of carbon emissions from 39.2 kilotons of waste. Other categories, such as mixed waste, plastic, paper, and plasterboard, have relatively low carbon emissions, with 101.8 tons, 78.3 tons, 14.5 tons, and 116.5 tons, respectively.

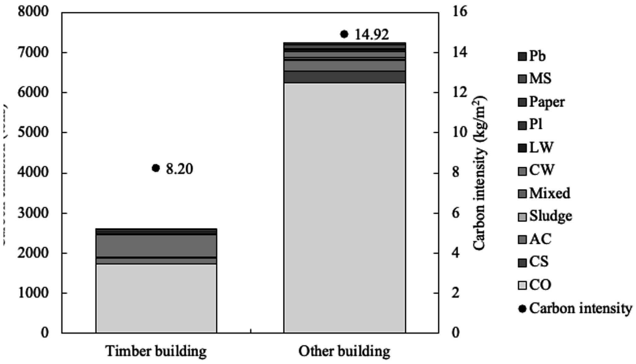

Fig. 6. The carbon emission of demolition process

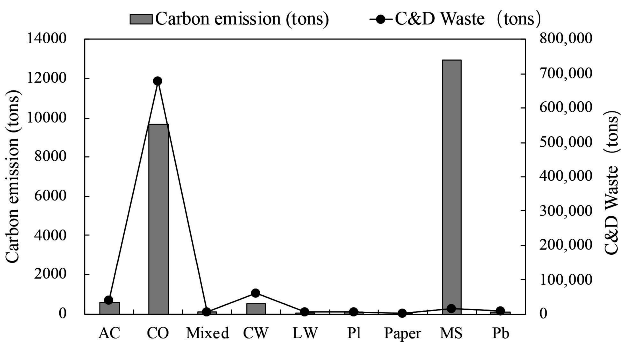

Fig. 8. The carbon emission of intermediate treatment

4. Discussion

4.1 Carbon reduction benefits

Based on Zhao's research[8], we calculated the carbon emissions of new materials equivalent to recycled products and compared them with the full lifecycle carbon emissions of the recycled products. The difference between the two is defined in this paper as the carbon reduction benefit of recycling C&D waste. Fig.9 illustrates the carbon reduction benefits achieved by the city through waste recycling.

In total, the city recycled about 820 kilotons of construction material waste in 2019, which means that the same amount of new material was saved. However, the proportion of material reuse is very low, only 0.36%, and recycling is mainly recycling. The life cycle carbon emission of waste including recycling process is shown on the right side of Fig.9, and the total carbon emission is 34.9 kilotons. Producing the same amount of new material would emit 45.8 kilotons of CO_2. This shows that the city has actually generated about 9.9 kilotons of carbon emission reduction benefits by recycling C&D waste, and proves that recycling waste not only produces environmental benefits from the perspective of saving resources, but also contributes to the sustainable development of the city from the perspective of reducing carbon emissions

From the perspective of various types of waste, the conclusions of this study are somewhat different from those of previous studies. Peng[10] believes that concrete blocks and bricks have strong carbon emission reduction

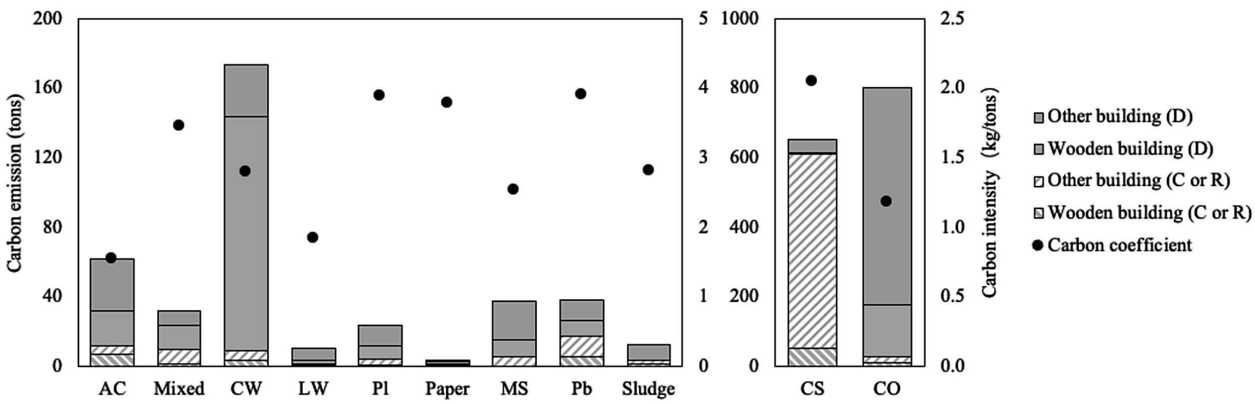

Fig. 7. The carbon emission of waste transportation

potential, while ceramics and glass have lower carbon emissions. This is caused by different research perspectives. Previous studies have focused more on the material itself and calculated the carbon potential based on the original nature of its waste as a building material. For example, using the carbon emission factor of cement to calculate already used concrete is an ideal study because the use of building materials is often irreversible. This paper focuses on the practical use of recycled waste. For example, concrete blocks are recycled and used as aggregates, and the corresponding new material is gravel. Cement has a much higher carbon emission factor than crushed stone. In conclusion, different research perspectives lead to different results.

4.2 Implications

This study examines the generation, flow, and carbon emissions associated with C&D waste in the city. It also compares the environmental impact of recycled products versus new products, revealing key findings from the analysis.

The city generates substantial C&D waste during construction, renovation, and demolition activities. The city enforces strict waste management regulations, resulting in high recycling rates, particularly for concrete blocks, metals, and other major waste types, which are recycled at over 95%. This achievement indicates that illegal dumping is no longer a significant issue. The focus should now shift towards enhancing the efficiency and profitability of recycling processes.

The study reveals that construction material waste primarily results from the disintegration process. Among C&D waste, concrete blocks constitute the largest volume and generate significant carbon emissions during disposal. Despite the simplicity of recycling concrete blocks, which essentially involves crushing them and converting them into aggregate, its current methods may be counterproductive to reducing carbon emissions. The carbon emissions associated with recycled concrete aggregates are higher than those of mined gravel. Additionally, the city's demolition process has a higher carbon emission efficiency compared to other

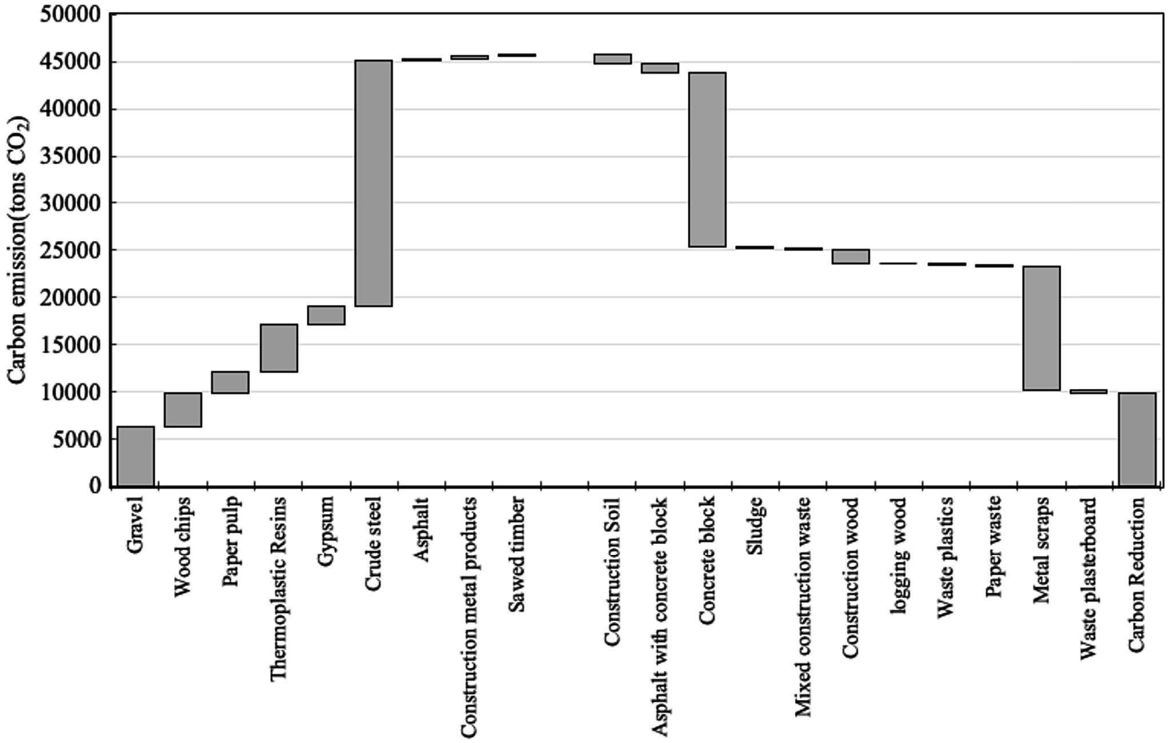

Fig. 9. Carbon reduction benefits of recycling waste

cities, underscoring the need to develop lower-carbon recycling technologies and reduce emissions in demolition processes as part of sustainable construction industry practices.

Previous research, such as studies by Colangelo et al. on the environmental impact of recycled concrete aggregates and Hafner & Schäfer[11] on modular building demolition, has assessed C&D waste management and its environmental impact[12]. However, these studies have not thoroughly detailed the flow of C&D waste or considered the capacity reduction and re-sourcing methods in the treatment process. This study addresses these gaps by: (1) exploring the generation and flow of C&D waste and identifying key waste types; (2) accounting for the carbon emissions and reduction potential of urban-scale C&D waste management.

4.3 Limitation

This paper uses questionnaires and interviews to obtain the energy consumption of building deconstruction enterprises and estimate the carbon emissions of the deconstruction process. However, it fails to differentiate by building structure, and the data are insufficient. The waste intermediate treatment process is intricate, and although detailed research was conducted, some processes were simplified, such as equating intermediate treatment products with new materials, so the estimated carbon emissions from intermediate treatment are underestimated. In the future, the process of waste treatment needs to be explored in more detail, and the products of waste treatment should be calculated to finished components to make carbon emission estimation more accurate.

5. Conclusion

This study used a life cycle assessment approach to assess the C&D waste generated from urban construction activities in Japan and its impact on the environment. In addition, the disposal and flow direction of demolition and construction waste are classified. Based on IPCC methods and input-output models, differences in carbon emissions between recycled and new materials were found. On the basis, the generation of C&D waste are compared, and the carbon reduction potential in the process of urban building disintegration is proposed.

The main findings are as follows: (1) In 2019, the city's construction waste was about 1.28 million tons, of which construction material waste accounted for the vast majority, and the waste recycling rate was over 95%. (2) Due to the large volume and high energy consumption of concrete and metal in the recycling process, they are the main contributors to carbon emissions in the recycling process. This shows that concrete recycling is not conducive to reducing carbon emissions, and its recycling technology needs to be improved. (3) LCZ results show that the carbon emissions of building decomposition and waste recycling have reached carbon balance, and the carbon emissions reduced by saving and remaining new materials is 9880 tons.

As a developed country, Japan is actively engaged in construction activities while also grappling with the issue of a large number of vacant houses. Therefore, building deconstruction and waste utilization have become crucial research topics with significant potential to impact urban environments and social development. This study evaluates the waste management process of construction debris in a specific city and its environmental effects. The findings will provide valuable insights for researchers and urban management authorities to develop targeted building management policies.

6. Reference

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