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Recycling Paths of Construction Waste from a Green and Low-carbon Perspective

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Abstract With the rapid advancement of construction industry and urban renovation, residential areas, office areas, commercial areas, and other buildings are densely distributed in cities. With the gradual deterioration of urban infrastructure and the increase of demolition projects for old construction sites, a large amount of construction waste has been produced. In this study, the "dual carbon" goal was as the core orientation, the generation characteristics, classification standards, management status, and existing problems of construction waste in China were systematically analyzed. Through literature research, field investigation, and data analysis, the negative impacts of construction waste on the environment, economy, and social development were discussed, and then the technical paths for the reuse of construction waste were analyzed, mainly covering source reduction and classification management, key technologies for resource processing, and comparative analysis of different processing modes. The aim is to provide theoretical references and practical guidance for promoting the green, low-carbon, and sustainable development of construction industry.

Keywords Construction waste, Recycling and utilization, Green and low carbon, Circular economy
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China is the world's largest construction market. Since the reform and opening up, China's urbanization construction has entered a stage of rapid development, and it is currently at the peak of large-scale urbanization and infrastructure construction. The number of newly-built, renovated, and demolished projects remains large. The large-scale construction of construction industry has injected new vitality into the prosperity of cities and effectively promoted the development of the industry itself. However, there are also many resource and environmental risks hidden behind it. The large-scale urban construction activities of humans have led to the continuous emission of carbon dioxide and its continuous accumulation in the atmosphere, and the resulting global warming and other environmental hazards are irreversible. During the urbanization process, the construction waste generated during the demolition and reconstruction of a large number of old buildings has become the focus of many researchers. According to statistics, 30% of global urban solid waste comes from China, of which construction waste accounts for 40% of the total urban solid waste, and its annual output is growing at a high speed, putting great pressure on urban environmental carrying capacity[1]. Under the dual constraints of resources and the environment, the traditional linear development model of "exploitation-production-disposal" has made the depletion of natural resources, the occupation of land resources, and environmental pollution problems increasingly prominent.

Facing the "dual carbon" goals proposed by the country and the requirements for "zero-waste cities", actively implementing energy-related policies[2] to promote the transformation of construction industry towards green, circular, and low-carbon is an urgent need to solve the problem of resource waste in China. Based on the existing research results[3-4], countermeasures and suggestions for promoting the efficient reuse of construction waste were proposed from the aspects of policy regulations, technical standards, market mechanisms, and management models, and the subsequent research directions for the resource utilization of construction waste and construction of "zero-waste cities" were analyzed. This study can enrich the theories related to construction waste management and provide academic support for the application of circular economy in the construction field. In addition, it can also provide decision-making basis for construction units and government departments to formulate waste management strategies, help to reduce construction cost, reduce environmental hazards, cultivate new economic growth points, promote the sustainable development of construction industry, and has important practical significance.

1 Demands for construction resources and the status of construction waste in China

1.1 Demands for construction resources

At present, China is in a stage where industrialization, urbanization and modernization are advancing simultaneously. During this special development period, the demands for construction resources continue to increase along with the development of social economy and the improvement of residents' living standards. Coupled with the basic national condition of a large population base, the consumption of construction resources is rapid, and the total consumption is large.

Currently, the unit energy consumption of high-energy-consuming industries such as steel, power, and cement in China is on average about 20% higher than that of the world's advanced level. The material consumption of major raw materials for construction such as steel and cement is 5-10 times higher than that of developed countries. The construction area of buildings in China, both under construction and completed, nearly doubled every 5 years (Fig.1). In 2019, the sales revenue of cement industry in China reached 1.013 2 billion yuan, and the annual compound growth rate of the industry from 2020 to 2024 was approximately 8.98%. China's GDP in 2015 is as the benchmark, and the demand for cement in China from 2020

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to 2040 can be predicted based on cement consumption per ten thousand dollars of GDP and GDP output in that year (Fig.2). Sand and gravel are the core aggregates of concrete, and its market demand grows rapidly with the continuous increase of cement usage.

The above analysis visually reflects that China's construction scale is huge, and the demand for basic construction resources such as cement and sandstone is in a stage of high total quantity and high growth rate. This special development stage and the large population situation determines that there is a situation where there is a large demand for construction resources and a large amount of various garbage and waste are generated simultaneously. Solving the problem of effective supply of construction resources has become a key issue in the process of social development.

1.2 Status of construction waste

As the demand for construction resources in China is growing rapidly, the production of construction waste has also increased accordingly. The annual production of construction waste in China is approximately 3.5 billion t. According to statistics, the production of engineering waste in China in 2020 was approximately 448–1,196 million t, and the production of demolition waste was approximately 1,487–2,417 million t, while the production of renovation waste was approximately 247–494 million t. If market space is estimated based on a benchmark of 30–60 yuan/t, the market space for construction waste treatment in China in 2020 was approximately 65.4–246.4 billion yuan.

According to statistics, the production of building demolition waste, building construction waste, and building renovation waste accounts for 51%, 48%, and 1% of the total quantity of construction waste, respectively. It can be seen that building demolition and building construction are the main sources of construction waste. The annual production of construction waste in China is as high as 1.8 billion t, but the resource utilization rate is less than 5%, while the recycling utilization rate of construction waste in some developed countries has reached over 90% (Fig.3).

2 Survey on the generation and disposal of construction waste in building projects

2.1 Sources and classification of construction waste

The main sources of construction waste in building projects include land excavation, demolition of old buildings, construction process, and losses during the production and transportation of building materials. According to the composition and usability of construction waste, it can be classified into four categories: recyclable waste, reusable waste, hazardous waste, and mixed waste. Recyclable waste mainly contains metal products such as steel bars and profiles, wood products such as formwork and boards, as well as plastics, glass, and intact bricks. Reusable waste mainly consists of concrete blocks, waste bricks and crushed stone and soil, among which crushed stone and soil can be used as recycled aggregates after being crushed and screened. Hazardous waste includes waste paint, waste coatings, waste asphalt, and waste fluorescent tubes, etc., and such waste needs to undergo professional and special treatment. Other mixed waste is complex in composition and difficult to separate.

2.2 Current models for the disposal of construction waste in China

Currently, there are several models for the disposal of construction waste from building projects in China. Among them, the extensive disposal method still dominates, while the resource disposal accounts for a relatively low proportion.

Firstly, the core dominant method is illegal dumping and stacking. Due to the imperfect planning and layout of solid waste treatment plants in cities, the distribution of construction waste is unreasonable. In addition, the environmental awareness of the public and construction enterprises is weak. In order to reduce transportation cost and time consumption, some entities still generally adopt this primitive solid waste disposal method.

Secondly, simple landfill is also the main method of solid waste disposal in China at present. This method means collecting solid waste on the construction site in accordance with the law and transporting it to nearby landfill sites for disposal. Compared with nearby illegal dumping, the pollution to the environment is reduced to some extent. However, there are still resource waste, potential safety hazards and environmental secondary pollution risk.

Compared with the above two models, initial recovery and resource-based processing are relatively better methods, but their application proportion is still low. Initial recovery is mostly carried out by individual entrepreneurs, and the valuable parts of waste materials are only recovered. There are problems such as low recovery rate and unstandardized operation. Resource processing means establishing fixed or mobile treatment plants to professionally process the waste. Currently, the application scale of this mode is still small.

2.3 Drawbacks of traditional disposal methods of construction waste

Firstly, simply stacking construction waste in the open air or directly burying it on the site not only occupies a large amount of land resources but also pollutes soil, air and water body, posing potential safety hazards[5]. In China, most construction waste is still piled up or buried at will, and occupies a huge area of land. According to international calculation methods, approximately 1 hm^2 of land is occupied by landfilling of 150,000 t of construction waste, and the annual area of land occupied by landfilling of construction waste exceeds 6,667 hm^2 in China. The construction waste piled up in the open air will gradually seep into soil over

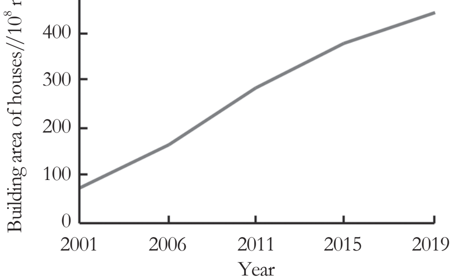

Fig.1 Growth of housing area in China

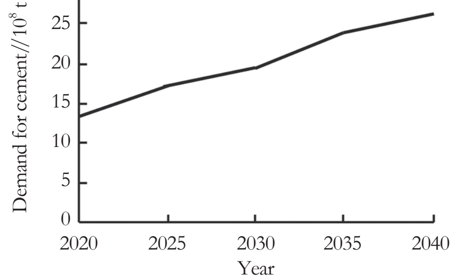

Fig.2 Predicted demand for cement in China from 2020 to 2040

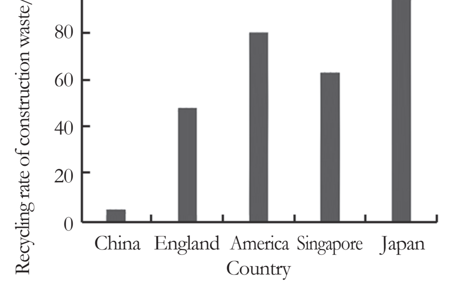

Fig.3 Utilization rate of construction waste in various countries

time and under external pressure, changing the composition of soil and destroying its structure, thereby reducing its productivity.

Secondly, the random stacking of construction waste not only occupies urban space but also is incompatible with urban development plans, becoming a prominent problem restricting urban development. During rainfall, if construction waste is not promptly handled, dirty water and soil will overflow, causing serious impacts on urban environment.

Thirdly, it will seriously affect air quality. During the stacking process of construction waste, due to the dual effects of temperature and humidity, some organic substances will decompose and produce harmful gases, causing secondary pollution to the air.

For instance, the total construction area of a certain construction project in Xi'an is 91,376 m^2. During the construction process, about 274,125 t of materials such as reinforced concrete, brick and stone were used, and a total of 4,782.8 t of construction waste were generated, of which reinforced concrete accounts for 74%.

From the above analysis, it can be seen that the traditional disposal methods for construction waste in China have caused a series of problems such as environmental pollution and resource waste. The utilization rate of construction waste for resource recycling is low, and achieving low-cost resource-efficient processing of construction waste has become a key direction for the development of China's construction industry.

3 Reuse technology pathways of construction waste

With the acceleration of urbanization in various countries, the energy demand for the production and transportation of construction materials continues to increase, and the difficulty of carbon emission control is constantly rising. To actively respond to this challenge, decarbonization and emission reduction in the industry of construction materials have become a key content that cannot be ignored in current research. Utilizing construction waste to produce recycled materials as an alternative to natural gravel not only alleviates carbon emission pressure and reduces environmental pollution, but also saves resources and energy, which is in line with the current requirements of society for the development of green concrete[6-7]. The management of construction waste is not a simple end-of-pipe treatment, but should follow the priority sequence of "reduction, resource utilization, and harmless treatment", and establish a full life cycle management system from the source to the end.

3.1 Source reduction and classification management: the most cost-effective and environmentally beneficial approach

"Prevention is superior to remediation". Taking effective control measures before the generation of waste is the key to fundamentally solving the problem of construction waste. Source reduction and classification management are the direct embodiment of the circular economy concept in the construction stage, and can achieve the most significant environmental and economic benefits.

3.1.1 Strategies of source reduction during the design stage. Design decisions directly affect the production and type of waste generated at the construction site. By optimizing the design plan, it is possible to significantly reduce the production of waste at the source.

(1) Green design and refined design. (i)Application of building information modeling (BIM) technology. BIM technology has significant advantages in optimizing resource allocation and management during construction by constructing a three-dimensional digital model of buildings[8]. During the design stage, using BIM technology for collision detection can identify design conflicts between architecture, structure, mechanical and electrical specialties in advance, and avoid the generation of a large amount of waste due to rework and reconfiguration during construction. At the same time, based on the BIM model, precise engineering quantity calculations can be completed to provide accurate data for material procurement and reduce resource waste caused by excessive procurement. (ii) Modular coordination and standardized design. Promoting modular and standardized design for buildings can make the dimensions of building components and parts coordinated and unified, effectively improve material utilization rate, and reduce waste from on-site cutting and processing. For example, prioritizing the matching of standard specifications for common materials such as gypsum board and cement fiberboard during designing can avoid unnecessary cutting waste at the source. (iii) Material-saving design. On the premise of ensuring the safety of projects, high-strength concrete and high-strength steel bars are used to optimize structural section dimensions. In non-load-bearing structures, promoting the use of lightweight partition boards and other new materials to replace traditional clay brick masonry can not only reduce structural load but also reduce the generation of construction waste.

(2) Application of new construction methods. (i) Prefabricated buildings. Partial or all components of a building are produced in factories, and then transported to the construction site for assembly. This method transfers a large amount of on-site wet work to the factories, which can significantly reduce waste such as concrete, mortar, and broken bricks generated during on-site formwork erection, pouring, and masonry[9]. Studies have shown that using prefabricated construction methods can reduce construction waste by more than 60%, and the factory production environment is more conducive to the centralized classification and recycling of waste. (ii) Steel structure buildings. The processing accuracy of steel structure components is high, and on-site installation mainly uses bolt connections or welding, so almost no solid waste is generated. Even during the demolition stage of buildings, steel can be almost fully recycled and reused, so it is a typical green building material.

3.1.2 Fine-grained classification management during the construction phase. Even with the most optimized design, waste is inevitably generated during the construction process. Therefore, implementing effective classification management at the construction site is the prerequisite for ensuring the effect of subsequent resource utilization.

(1) Principle of "on-site classification" and facility configuration. (i) Developing a classification plan. In the construction organization design, the *Management Plan of Waste at the Construction Site* is specially prepared to clearly define the classification categories of waste, collection containers for each type of waste, storage area, the person responsible for management, and disposal process. (ii) Configuring classification collection facilities. At key positions such as the operation area, material storage area, and entrances and exits of the construction site, clearly marked and color-coded classification garbage bins or storage pools are set up. For example, blue, green, gray and red bins are used to collect metal waste, wood waste, concrete debris, and hazardous waste, respectively. Clear visual guidance is crucial for improving the accuracy of workers' classification disposal. (iii) Strengthening publicity and education and insti-tutional constraints. Continuous environmental protection education and classification operation training for managers and front-line workers are conducted to enable them to fully understand the importance of waste classification and master correct operation methods. Meanwhile, the implementation of waste classification is linked with the

performance assessment of teams, and an effective incentive and restraint mechanism is established.

(2) Digital management and process monitoring. (i) Application of Internet of Things (IoT) technology. Weighing sensors and RFID tags are installed on classification garbage bins. When the garbage bins are about to be full, an automatic reminder will be sent to the managers, and the production of each type of waste will be recorded in real time, providing data support for waste management and cost accounting. (ii) Drone inspection. Drones are used regularly to conduct aerial photography of the construction site, quickly identify areas with improper waste storage and unclear classification, facilitate timely rectification by managers, and achieve effective monitoring of large-scale construction sites.

3.2 Key technologies for resource utilization to enhance the value of recycled products

The construction waste that has been classified and collected should be processed and treated by a series of physical and chemical processes, and converted into recycled building materials with market value. This is the core step in achieving the resource utilization of waste materials.

3.2.1 Pre-treatment and sorting technologies. Efficient sorting is the foundation for ensuring the quality of subsequent recycled products. Its core objective is to remove impurities from waste materials. It is mainly divided into primary sorting and mechanical sorting. Primary sorting, namely manual sorting, means that workers manually pick out large pieces of wood, plastic, paper, etc. which are easily identifiable beside the conveyor belt. This method is currently the most commonly used and has a lower cost, but the sorting efficiency is not high, and workers' working environment is harsh. Mechanical sorting is a sorting system formed by integrating multiple technologies. Technologies such as crushing, screening, magnetic separation, air separation, and hydrocyclone flotation are adopted to select recycled materials that meet the requirements. The sorting efficiency and accuracy are much higher than manual sorting.

3.2.2 Reinforcement and modification technologies of recycled aggregates. The recycled aggregates obtained through simple crushing and screening have a large amount of old cement mortar adhering to their surfaces, resulting in defects such as high porosity, high water absorption rate, high crushing index, and weak interface bonding with new cement paste, which severely limits their application in structural concrete. Therefore, the recycled aggregates need to be strengthened to improve their performance. The reinforcement technologies of recycled aggregates can be divided into physical reinforcement and chemical reinforcement. Physical reinforcement includes methods such as particle shaping and heating grinding, while chemical reinforcement contains methods such as polymer immersion, sodium silicate solution immersion, and carbonation treatment. After reinforcement treatment, the density, strength, and other properties of the aggregates are significantly improved, and water absorption rate and other indicators are effectively reduced. After reinforcement treatment, some aggregates can also achieve CO_2 fixation and possess certain "carbon capture" benefits.

3.2.3 High-value application paths of recycled products. Properly processed recycled aggregates and other selected materials can be processed to produce various building materials. According to the performance of products, their application paths can be divided into low, middle and high levels, namely downgrade utilization, equal utilization, and high-value utilization. Downgrading utilization mainly means applying recycled construction waste and graded crushed stones to the base layer, sub-base layer of roads, or for site leveling, foundation backfilling, etc. This method has a large amount of waste material disposal and low technical requirements. Recycled filler technology means the processed waste materials are transformed into nutrient soil for landscaping or used as fill material for land reclamation.

Equal utilization includes the production and application of recycled concrete solid bricks, blocks, recycled permeable bricks, curb stones, and recycled dry-mixed mortar. Among them, recycled permeable bricks are made by utilizing the higher porosity of recycled aggregates, and can be applied to the pavement of roads during the construction of sponge cities, which has good ecological benefits.

High-value utilization is the current focus of technological research, mainly including the research and application of structural recycled concrete and recycled cement products. Structural recycled concrete uses high-quality recycled coarse aggregates that have been strengthened to partially or entirely replace natural stones, and is formulated for use in concrete for buildings, bridges, etc., which requires strict control of the performance of recycled aggregates. Systematic mix ratio design and experimental verification are conducted to ensure that its workability, mechanical properties, and durability meet the requirements of the specifications. In China, *Technical Specification for Application of Reclaimed Aggregate* (JGJ/T 240-2011) and other standards have provided technical basis for the application of recycled concrete in structural engineering.

To produce recycled cement products, waste concrete and bricks and tiles are fully processed and ground to obtain recycled micro-powder with certain activity, which is used as a substitute raw material for cement production or as a mineral admixture in concrete. This is one of the ultimate goals of fully utilizing the components of construction waste. Currently, it is still in the stage of research and exploration.

3.3 Comparison between mobile processing and fixed processing plant modes

3.3.1 Mobile processing mode. Mobile processing mode means integrating the equipment for feeding, crushing, screening, and iron removal onto one or several movable chassis, and forming a flexible transferable production line. This mode is suitable for projects with limited construction sites and where fixed processing facilities cannot be established. It is commonly seen in large-scale demolition projects, urban renewal areas, and multiple scattered small and medium-sized project clusters.

The core advantage of this mode is on-site processing, with extremely low transportation cost. Processing and treatment are carried out directly at the waste generation site, and large pieces of waste are converted into uniformly sized recycled aggregates, significantly reducing the volume of waste and effectively lowering the cost of transporting it to disposal sites. At the same time, it is highly flexible, and can quickly enter and withdraw from the site according to the project schedule. However, this mode also has obvious shortcomings. Due to the size of the equipment, the processing capacity of a single machine is usually lower than that of a fixed processing plant, and the processing capacity is relatively limited. Because of space constraints, it is difficult to integrate complex sorting and strengthening equipment. The products produced are mainly made of low-grade aggregates, and their quality is average. Most of the operations are carried out in the open air, and there are high requirements for noise and dust control at the construction site. The difficulty of environmental control is considerable.

3.3.2 Fixed processing plant mode. Fixed processing plant mode means building permanent or semi-permanent resource chemical plants of construction waste around a city, so as to centrally receive and process construction waste from various parts of the city. This mode is suitable for areas with high requirements for the quality of recycled products and a desire for high-value utilization. It is commonly seen in large cities where the production of construction waste is large and concentrated.

The advantages of this mode are quite obvious. Processing scale is large, and unit processing cost decreases with scale increase; it has large-scale and industrialization benefits. It can be equipped with complete sorting lines and aggregate strengthening equipment, and produces various specifications of high-performance recycled aggregates and building materials products, with high technical integration and excellent product quality. A closed factory can be built and equipped with efficient dust removal, noise reduction, and wastewater treatment systems. It is more environmentally friendly and has complete environmental protection facilities. It can serve as a regional construction waste treatment center, and forms a stable supply chain with building material enterprises. It is easy to build a complete industrial chain. The main disadvantages of this mode are as follows. The initial investment is huge, and the investment cost in land, factory buildings, and equipment is high. The transportation cost is high. The scattered construction waste in a city needs to be transported to fixed disposal sites, which incurs additional logistics cost and increases urban traffic pressure. There is a high demand for the stability of raw material supply, and the government needs to ensure the availability of stable and sufficient sources of construction waste through relevant policies.

3.3.3 Strategies of mode selection. The choice of treatment modes of construction waste depends on various factors such as the source, production, and transportation distance of waste and land cost. In practical applications, "mobile and fixed modes" are often combined. For large-scale demolition projects, mobile equipment is used for on-site preliminary treatment in the early stage to break down and reduce the volume of large waste. Afterwards, the treated materials are transported to a fixed processing plant for deep processing and the production of high-quality recycled products. This combined mode can balance economic benefits and product value, and is one of the optimal paths for realizing the resource utilization of construction waste.

Overall, the recycling path of construction waste is a progressive system from "prevention" to "control" and then to "creation". Each link must be closely connected and work together in coordination to achieve the efficient resource utilization of construction waste.

4 Conclusion

Promoting the reuse of construction waste in building projects is a complex systematic undertaking and a profound industrial transformation in construction industry. This requires industry practitioners to shift from the traditional linear thinking to circular thinking, and to transform waste management from end-of-pipe treatment to full-process management. Through meticulous management during the design and construction phases, the generation of waste can be minimized to the greatest extent. The quality and value of recycled materials can be enhanced through efficient sorting technologies and deep processing techniques. Finally, by establishing a reasonable business model and diversified application paths, "resources in the wrong place" should be returned to the construction industry chain, ultimately closing the recycling loop of building materials and promoting construction industry towards true sustainable development.

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