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Application and performance evaluation of recycled building materials in civil engineering

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Abstract. The concept of renewable materials has received extensive advocacy and promotion in the ongoing development of the construction industry. Furthermore, emerging renewable building materials, such as bio-based composite materials, are continually evolving and gradually being incorporated into civil engineering applications. This paper focuses on the application and performance assessment of recycled building materials in civil engineering. As a crucial component of environmental protection and sustainable development, recycled building materials possess vast potential for application. In this article, the characteristics of common materials such as recycled concrete, recycled steel, and recycled glass are introduced, and their mechanical performance, durability, and other vital attributes are evaluated. Finally, the feasibility and challenges of recycled building materials are analyzed, along with discussions on sustainable development strategies and policy support. The comprehensive research results demonstrate the significant role of recycled building materials in promoting sustainable development in civil engineering, warranting increased support and promotion at the policy and societal levels.

Keywords: Recycled Building Materials, Civil Engineering, Performance, Assessment.

1. Introduction

With the increasing global awareness of environmental protection and the demand for sustainable development, the application of recycled building materials in civil engineering has gained significant attention. Recycled building materials are those produced through the recycling of waste materials or the utilization of renewable resources, offering advantages such as resource conservation [1], environmental friendliness, and economic benefits. In civil engineering, the utilization of recycled building materials, reduces the environmental impact of construction and enhances the sustainability and cost-effectiveness of projects. Concurrently, the performance evaluation of recycled building materials remains a crucial aspect of ensuring their safety and reliability. Hence, it is imperative to conduct a comprehensive analysis and evaluation of their application and performance.

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2. Application of Recycled Building Materials in Civil Engineering

2.1. Application in Concrete

The application of recycled building materials in civil engineering has become one of the critical directions of sustainable development. Among them, in the field of concrete, recycled aggregate and fly ash, as common recycled building materials, are receiving more and more attention. Recycling aggregate is the coarse aggregate recycled from construction waste, concrete debris and other resources, and recycled fly ash is the recycling product of the ash produced in the coal-burning process of power plants in cement and concrete production. These two kinds of recycled building materials can not only reduce the consumption of resources but also hope to improve the performance of concrete and reduce environmental pollution. In order to evaluate the application effect of recycled aggregate and fly ash in concrete, the following data in Table 1 are obtained [2].

Table 1. evaluates the application effect of recycled aggregate and recycled fly ash in concrete.

Experimental Samples	Concrete Type	Replacement Ratio	Compressive Strength (MPa)	Flexural Strength (MPa)	Density (kg/m³)
Sample A	Ordinary Concrete	0%	35.2	4.6	2400
Sample B	Ordinary Concrete	20%	38.7	5.2	2370
Sample C	Ordinary Concrete	40%	42.1	5.7	2330
Sample D	Recycled Aggregate Concrete	40%	39.5	5.4	2250
Sample E	Ordinary Concrete	20%	36.8	4.9	2400
Sample F	Recycled Fly Ash Concrete	30%	41.2	5.6	2300

From Table 1 above, it is evident that the utilization of recycled aggregates to partially replace traditional aggregates in concrete production can lead to a certain degree of enhancement in both compressive and flexural strength. Additionally, the incorporation of recycled fly ash into concrete contributes to the improvement of its mechanical properties. Moreover, the application of these two types of recycled building materials can also reduce the density of concrete, consequently reducing the structural self-weight. This not only conserves raw materials but also enhances the sustainability of civil engineering projects.

2.2. Application in Steel

Recycled steel, derived from reprocessing discarded steel materials, serves as a sustainable building material. In conventional steel production processes, substantial energy and resources are consumed, leading to significant waste and emissions that burden the environment. However, the application of recycled steel can effectively reduce dependence on natural resources, lower carbon emissions, and diminish waste generation. This aligns with the objectives of resource recycling and environmental protection. In civil engineering, recycled steel can be utilized for manufacturing key components such as structural frameworks, beams, columns, supports, and bridges. It provides reliable structural support for projects while decreasing demand for raw ores and promoting the green development of the steel industry [3].

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Reinforcement bars (rebars) play a critical role in the strengthening framework of concrete structures within civil engineering. Traditional rebar production involves energy-intensive steelmaking processes, yet the implementation of recycled rebars significantly reduces carbon emissions and energy consumption [4]. Recycled rebars can be reprocessed from discarded resources such as demolished buildings, old bridges, and discarded concrete structures. This reduces the need for virgin resources and mitigates landfill waste. Recycled rebars undergo rigorous quality and performance testing and certification, ensuring they meet the strength, ductility, and durability requirements of civil engineering projects. Thus, incorporating recycled rebars benefits environmental protection and resource conservation and ensures the safety and reliability of engineering projects.

2.3. Application in wood

The use of reclaimed timber in civil engineering is one of the key measures for sustainable construction and environmental development. Recycled wood is the recycled materials used from waste wood, building demolition and surplus materials in the production process of wood products. Compared with traditional wood harvesting [5], the application of reclaimed wood can effectively reduce the consumption and destruction of forest resources and reduce energy consumption and emissions in the process of wood production, thus reducing the carbon footprint and slowing down climate change. In civil engineering, recycled timber is widely used in structural and decorative parts such as floors, walls, beams and furniture, providing beautiful, environmentally friendly and economical choices for engineering. It is one of the important application forms of recycled wood in civil engineering. The generative fiber board is made by mixing waste wood or wood fiber with adhesives such as synthetic resin [6], and then through high temperature and pressing. In civil engineering, recycled fiberboard is often used for the manufacture of indoor floors, walls, ceilings and furniture. To evaluate the application of recycled fiber board in civil engineering, the basic physical parameters are listed in Table 2 below [7].

Table 2. Basic physical parameters of the regenerated fiberboard.

Experimental Samples	Density (kg/m³)	Flexural Strength (MPa)	Compressive Strength (MPa)	Water Absorption (%)
Sample A	750	32.5	42.1	6.2
Sample B	820	28.3	38.7	5.8
Sample C	780	30.7	40.2	6.0
Sample D	800	29.9	39.5	5.9

The recycled fibrillboard has reasonable density and excellent mechanical properties in civil engineering, especially its stable and flexural strength and compressive strength. At the same time, the water absorption rate of the recycled fiber board is also low, indicating that it has better durability and moisture resistance [8]and is suitable for the environment with higher indoor humidity. The wide application of recycled wood and the excellent properties of recycled fiberboard bring new opportunities for sustainable development in the civil engineering field. The application of recycled wood is not only conducive to the protection of natural resources and the environment, but also helps to promote the construction industry to the green and low-carbon direction transformation. At the same time, the recycled fiberboard, as an environmentally friendly interior decoration material [9], not only provides an excellent decorative effect, but also a better guarantee for the indoor air quality and health. However, some technical and economic challenges, such as production cost, quality standards and certification system, still need to be addressed in promoting the application of recycled wood and recycled fiberboard. Therefore, further research and industrial support are necessary to promote the

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sustainable development of recycled wood and recycled fiberboard, and to promote the development of civil engineering to a more environmentally friendly and sustainable direction.

3. Performance Evaluation of Recycled Building Materials

3.1. Mechanical Performance Evaluation

The performance evaluation of recycled building materials is crucial in civil engineering, particularly strength testing and flexural performance testing, to assess their mechanical properties.

3.1.1. Strength Testing. Strength testing is a significant approach to gauging the ability of recycled building materials to withstand external loads. Common evaluation metrics during testing include compressive strength, tensile strength, and shear strength, among others. By applying gradually increasing pressure or tension using standard testing equipment, the strain and deformation of recycled building materials under different loads can be measured, enabling the calculation of corresponding strength values [10].

3.1.2. Flexural Performance Testing. Flexural performance testing assesses the deformation and failure behavior of recycled building materials when subjected to bending forces. In this type of testing, we typically apply three-point or four-point bending loads using testing equipment, measure the deflection and strain of recycled building materials under different loads, and thus determine their flexural performance.

Suppose the flexural performance of various samples of recycled building materials has been tested, yielding the data shown in Table 3 below:

Table 3. The bending performance assessment data for samples of different recycled building materials.

Sample	Flexural Strength (MPa)	Maximum Deflection (mm)
A	12.3	5.8
B	10.9	6.2
C	13.5	5.5
D	11.8	6.0

From the given data, it can be observed that the flexural strength and maximum deflection of these recycled building material samples fluctuate within a certain range. This indicates that they possess good deformation and load-bearing capabilities when subjected to bending loads. Adequate flexural performance is crucial for stability and durability of structures in civil engineering, and thus, these data results suggest favorable flexural behavior of these recycled building materials [11].

3.2. Durability Performance Evaluation

Durability performance evaluation is a crucial process that assesses the performance of recycled building materials under prolonged usage and exposure to environmental conditions. Durability performance evaluation includes two main aspects: durability testing and corrosion resistance testing. The significance and role of these two testing methods are elaborated below.

3.2.1. Durability Testing. Durability testing is a method to evaluate the long-term durability of recycled building materials under different external environmental conditions. By exposing recycled building material samples to harsh conditions simulating real-world usage, including climate, humidity, temperature, UV radiation, and more, one can observe the performance changes of the materials after extended exposure. This may include surface deterioration, color fading, cracking, and loss of quality. Durability testing simulates various natural and human-induced factors that recycled building materials might encounter in real-world applications, helping to assess material durability and lifespan. Durability testing data for different samples are presented in Table 4 below: [12]

Table 4. Different samples derive durability test data.

Sample	Surface Condition after 12 Months of Exposure
A	Slight cracking and color fading on the surface
B	Surface remains mostly unchanged, with minor wear
C	Significant deterioration of the surface, substantial loss of quality
D	Slight cracking on the surface, with minimal change in quality

3.2.2. Corrosion resistance performance test. Corrosion resistance testing is a method to assess the resistance of recycled building materials in corrosive media. In construction engineering, recycled building materials may be exposed to corrosive substances such as acid, alkaline and salt, for example, they may be eroded by seawater in the Marine environment, while in industrial areas they may be affected by acid-alkali waste liquid. The corrosion resistance test evaluates the corrosion resistance and durability of recycled building materials by soaking or spraying a sample of corrosive media to observe their corrosion over a certain period of time. The corrosion resistance test is shown in Table 5 below.

Table 5. Test the corrosion resistance tests of different samples.

Sample	Surface Condition after 48 Hours of Corrosion
A	No noticeable change, good corrosion resistance
B	Slight surface corrosion traces, fair corrosion resistance
C	Significant surface corrosion, poor corrosion resistance
D	Minor corrosion traces on the surface, good corrosion resistance

Sample A performed well in the durability test, with relatively good surface condition and good corrosion resistance, showing high durability. Sample B performed better in the durability test, with general corrosion resistance and relatively reliable durability. Sample C is poor in durability testing, is significantly impaired, and has poor corrosion resistance, which may require improved material formulation or the use of preservative measures. Sample D performed well in the durability test, despite minor cracking, with less quality variation and good corrosion resistance. In conclusion, durability testing and corrosion resistance testing are key steps for the comprehensive evaluation of recycled building materials. Through these tests, we can understand the performance of recycled building materials in long-term use and in different environments, helping to optimize the material properties and ensure their sustainable application and long-term stability in civil engineering [13].

3.3. Sustainability assessment

Sustainability assessment is a method to assess the environmental impact and sustainability of recycled building materials throughout the lifespan. Among them, carbon footprint analysis and energy consumption assessment are two important aspects used to quantify the impact of recycled building materials on carbon emissions and energy utilization during the production, use and treatment stages.

3.3.1. Carbon footprint analysis. Carbon footprint analysis is a method used to assess the greenhouse gas emissions generated by recycled building materials throughout the life cycle. The production process of recycled building materials is accompanied by energy consumption and emissions of greenhouse gases such as CO2. Through carbon footprint analysis, these emissions can be quantified and converted into equivalent CO2 emissions to measure the carbon impact of recycled building materials. By reducing the carbon footprint, the negative impact of climate change can be reduced, and the low-carbon buildings and sustainable development goals can be achieved. For example, the distribution of carbon footprints of the four recycled materials is shown in Figure 1 below.

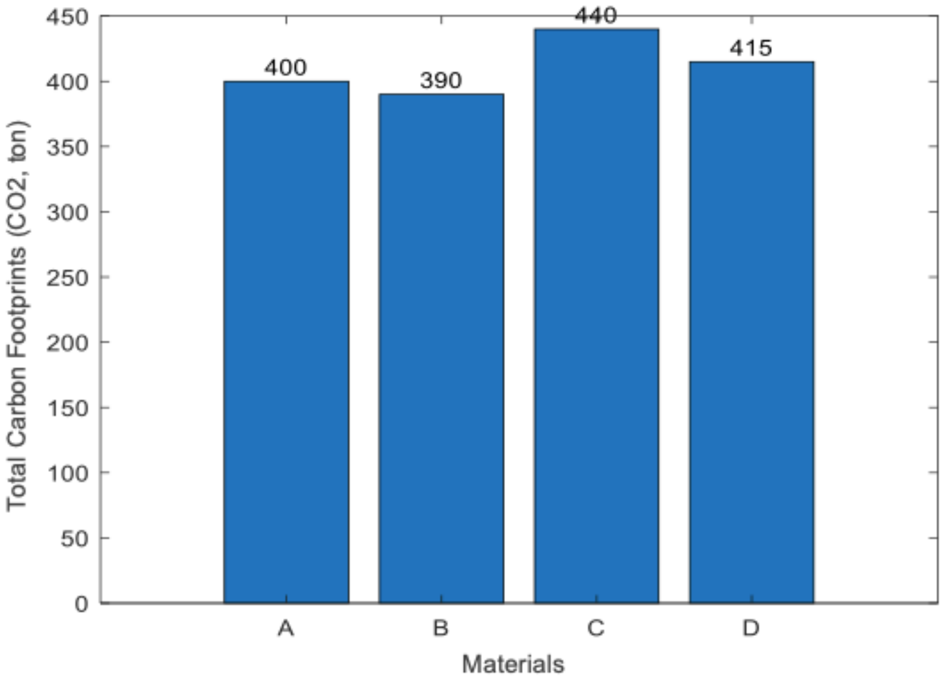

Figure 1. The distribution of carbon footprints of the four recycled materials.

Material C has the highest total carbon footprint of 440 tons of CO_2, indicating that high carbon emissions were generated during the production, use, and treatment of this material. The total carbon footprint of material B is slightly lower than material C at 390 tons of CO_2, indicating that less carbon emissions are generated during the life cycle of this material. The total carbon footprints of materials A and D are 400 t CO_2 and 415 t CO_2, respectively, intermediate between materials B and C, indicating that their carbon emissions are relatively close. Based on the carbon footprint data analysis, material B has the lowest carbon footprint, material C has the highest carbon footprint, and materials A and D have intermediate levels. These analysis results can provide a reference for considering the carbon footprint when selecting and using building materials, help to reduce the carbon emissions in the construction industry, and achieve more environmentally friendly and sustainable construction projects.

3.3.2. Energy consumption assessment. Energy consumption assessment is a method of assessing the amount of energy consumed during the production, transportation, use, and treatment of recycled building materials. The production and use of recycled building materials will involve the collection, conversion and transmission of energy, including forms of energy such as fossil fuels and electricity. Energy consumption assessments are designed to understand energy needs and energy efficiency during the life cycle of recycled building materials and to seek ways to reduce energy consumption to reduce resource consumption and environmental impacts and achieve sustainable energy utilization. The overall energy consumption curves of the 4 materials are shown in Figure 2 below.

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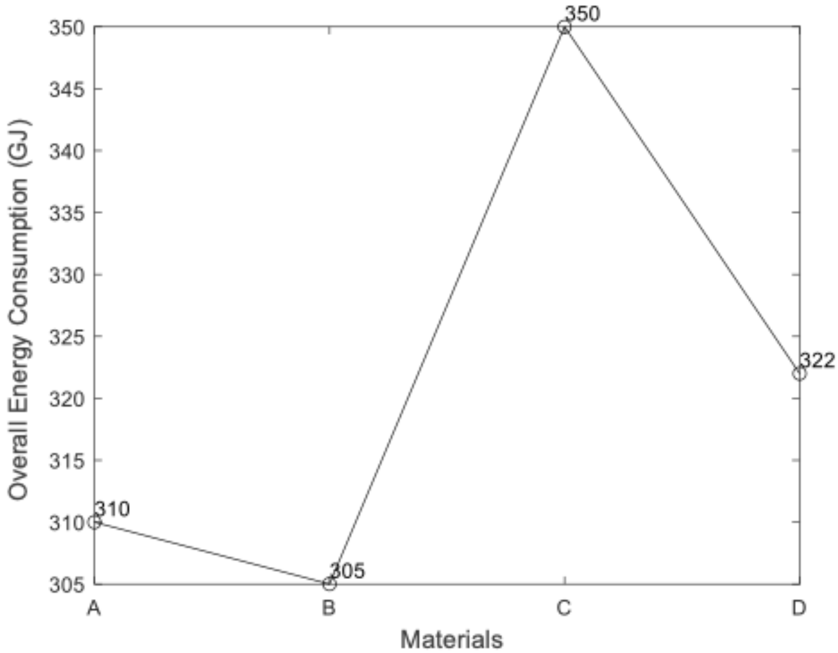

Figure 2. 4 Overall energy consumption curves of the materials.

4. Challenges and Opportunities for Recycled Building Materials

4.1. Technical Challenges

The quality and performance of recycled building materials pose significant technical challenges. The manufacturing process of recycled materials often involves the reuse of waste, potentially impacting their quality and performance. New technologies and processes must be developed to ensure that recycled building materials possess sufficient strength, durability, and other required performance characteristics to meet the industry's demands. The technological advancement of recycled building materials presents opportunities for the construction industry. Research and innovation can lead to the development of a wider range of recycled building materials using waste and renewable resources [14]. These materials can be used in various aspects of construction, such as structural components, insulation materials, and soundproofing materials, offering more choices for the industry. Furthermore, the utilization of recycled building materials can reduce reliance on finite resources, mitigate environmental pollution, and promote the development of a circular economy. The development of recycled building materials requires ongoing technological innovation. For instance, the development of novel materials can enhance the performance and quality of recycled building materials. Additionally, monitoring and controlling the manufacturing process should be strengthened to ensure that recycled building materials adhere to relevant standards and specifications. Moreover, leveraging digital technologies and advanced manufacturing processes can enhance the production efficiency and consistency of recycled building materials, further advancing their application and promotion.

4.2. Economic Challenges

Recycled building materials may face challenges in terms of initial investment and production costs. Compared to traditional construction materials, the production of recycled building materials often requires advanced technology and equipment, leading to higher initial investments. Particularly for some new recycled materials, their production processes and scale might be in their infancy, resulting in relatively higher production costs. Furthermore, the market share of recycled building materials

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might be relatively small, requiring overcoming economic barriers to establish supply chains and sales channels.

However, recycled building materials also offer numerous economic opportunities. With increasing global awareness of sustainable development, the market demand for recycled building materials is expanding. Governments and businesses are placing more emphasis on green buildings and environmentally friendly materials, leading to increased support and encouragement for recycled building materials. This growing market demand will foster the development and large-scale production of the recycled building materials industry, subsequently reducing production costs. Simultaneously, as technology advances, the research and innovation of recycled building materials continue, potentially resulting in higher-performing and more competitive products, enhancing market competitiveness. The promotion and application of recycled building materials will also create opportunities for creating more green jobs and economic growth, forming a sustainable development model.

4.3. Environmental Opportunities

4.3.1. Resource Circularity and Waste Reduction. One of the main characteristics of recycled building materials is their use of recycled or repurposed materials. By recycling waste or utilizing industrial byproducts, recycled building materials can transform waste into useful construction materials, achieving resource circularity. This practice helps reduce the extraction and consumption of natural resources, alleviating environmental pressure. Additionally, by reducing waste generation, recycled building materials contribute to lowering landfill and incineration-related environmental pollution, promoting sustainable waste management.

4.3.2. Carbon Emission Reduction and Climate Change Mitigation. Recycled building materials typically have lower carbon emissions during the production process. Compared to traditional building materials, the production process of recycled building materials often requires less energy and fossil fuels. Furthermore, through carbon footprint analysis and environmental impact assessments, the lifecycle carbon emissions of recycled building materials can be further optimized. This helps reduce the construction industry's energy demand, decrease greenhouse gas emissions, and actively address climate change. The widespread use of recycled building materials in green and low-carbon buildings also provides opportunities for achieving carbon neutrality and sustainable urban development.

4.3.3. Ecosystem Protection and Biodiversity. The use of recycled building materials often relies on natural resources like plant fibers and reclaimed wood, potentially positively impacting natural ecosystems. For example, the utilization of plant fibers can encourage the cultivation of plants and forest preservation, promoting ecosystem restoration and biodiversity conservation. The widespread application of recycled building materials also offers opportunities for ecological construction, integrating buildings more harmoniously with the natural environment, creating healthier and more sustainable living and working spaces [15].

5. Conclusion

In conclusion, the application and performance evaluation of recycled building materials in civil engineering are pivotal for promoting sustainable construction development. Through scientific performance assessment, the reliability and applicability of recycled building materials can be ensured, contributing to the sustainable development of the construction industry. In the future, continuous research, collaboration, and the advancement of performance evaluation techniques are needed to further drive the application and promotion of recycled building materials, injecting new impetus into the sustainable development of the construction industry. With the continuous advancement of materials science, we can anticipate the development of more renewable materials with outstanding performance, including attributes such as increased strength, enhanced durability, reduced weight, and greater transparency. For example, some scholars have begun to explore new functions of concrete recently, such as luminous concrete and exhaust gas absorbing concrete [16-19].

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