

Analysis and Selection of Hardscape Materials under the “Dual Carbon” Goals

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Abstract:

In the pursuit of the “Dual Carbon” goals, the landscape architecture industry plays an irreplaceable role. Through systematic research and optimized application of hardscape materials, the industry’s capacity for carbon emission reduction and carbon sequestration can be significantly enhanced. This paper analyzes hardscape materials and proposes a selection methodology for low-carbon alternatives, aiming to reduce carbon emissions from the source while strengthening the carbon sink function of landscape systems. It offers both a theoretical foundation and practical pathways for supporting the achievement of the “Dual Carbon” goals through landscape architecture.

Keywords:

Dual Carbon, Hardscape Materials, Low Carbon Emission, Carbon Sequestration Capacity

1. Introduction

Against the backdrop of increasingly severe global climate change, China has proposed the “Dual Carbon” strategic goals of achieving carbon peak by 2030 and carbon neutrality by 2060, charting a new course for ecological development in both urban and rural areas. To realize these objectives, the selection and application of hardscape materials during the construction process are particularly critical. It is essential to prioritize low-carbon and environmentally friendly materials, optimize construction techniques, and reduce energy consumption and carbon footprints. These measures will help lower carbon emissions, enhance carbon sequestration, promote the healthy development of the ecological environment, and thereby contribute to the fulfillment of the “Dual Carbon” goals.

2. Analysis of Low-Carbon Landscape Materials

Hardscape materials are primarily used in structures, roads, paving, rockeries, and water features, encompassing construction flooring materials, paving materials, cladding materials, and plumbing & electrical materials, among others. When studying low-carbon hardscape materials across their entire life cycle, it is essential to consider reducing energy consumption, improving energy efficiency, and lowering

carbon dioxide emissions throughout all stages: extraction and production, planning and design, construction and installation, and maintenance and operation. [1]

Regarding existing low-carbon landscape materials, this paper conducts a research analysis one by one based on six categories: brick, stone, wood, metal, glass, and other materials (including plastics and coatings)

2.1. Brick Materials

The carbon emission data of brick materials vary depending on factors such as raw material type, production process, energy consumption, transportation, construction methods, and lifecycle considerations. Carbon emission data for common low-carbon brick materials are presented in Table 1.

Table 1. *CO₂ Emissions and Characteristics of Various Brick Materials.*

Brick Types	Carbon Emission Range (kg CO ₂ /unit)	Characteristics
Traditional Fired Clay Brick	0.2–0.3 (Calculated based on the standard dimensions of 240mm × 115mm × 53mm)	Mainly originating from high-temperature firing (>1000°C) and fossil fuel consumption.
Fly Ash Brick	0.05–0.1	It utilizes industrial waste fly ash, reduces clay consumption, and typically employs an autoclaving process, resulting in lower energy consumption and carbon emissions.
Concrete Brick	0.1–0.15	The carbon emissions primarily originate from cement production; however, they can be reduced by optimizing the mix formulation and incorporating industrial wastes (e.g., slag).
Autoclaved Aerated Concrete Block (AAC)	0.08–0.12	It is lightweight with excellent thermal insulation properties. The autoclaving process used in its production requires relatively low energy consumption.
Straw Brick or Biomass Brick	0.02–0.05	It utilizes agricultural waste (e.g., straw) as raw material, resulting in minimal carbon emissions during production and exhibiting carbon sequestration potential.
Recycled Brick	0.03–0.07	It is manufactured using construction or industrial waste, reducing the need for raw material extraction and associated energy consumption.
Low-Carbon Cement Brick	0.06–0.1	It employs low-carbon cement (e.g., alkali-activated cementitious materials) as a substitute for traditional cement, significantly reducing carbon emissions.
3D-Printed Brick	0.04–0.08	The use of 3D printing technology enables precise material deposition, thereby minimizing waste and resulting in lower carbon emissions.

Based on the data presented above, it can be concluded that the use of low-carbon bricks (such as fly ash bricks, recycled bricks, and straw bricks) can reduce carbon emissions by 50%–90% compared to traditional fired clay bricks. Furthermore, by

integrating clean energy sources (e.g., solar, wind) and carbon capture technologies during production, shortening material transportation distances, and reducing energy consumption during construction, phase-specific carbon emissions can be further minimized.

2.2. Stone Materials

Outdoor stone materials mainly fall into three categories: natural stone, artificial stone, and recycled stone. The carbon emission data vary depending on factors such as stone type, quarrying methods, processing techniques, and transportation distance. For natural stone (e.g., granite, marble), carbon emissions mainly originate from quarrying, processing, transportation and construction, with the production stage (quarrying and processing) constituting the largest share. For instance, one study found that for granite, carbon emissions are predominantly generated during the production stage, accounting for 79.76% of the total, followed by the transportation stage at 19.46%, while the construction stage contributes only 0.78%. [2] Artificial stone (e.g., quartz stone, artificial marble) is produced by mixing natural stone fragments with materials like resin, and its carbon emissions depend on the specific production process. In contrast, recycled stone, processed from waste, generates emissions primarily during processing and transportation. Consequently, its emissions are significantly lower than those of natural and artificial stone .(As shown in Table 2)

Table 2. CO₂ Emissions of Various Stone Materials.

Stone Types	Carbon Emission Range (kg CO ₂ /ton)	Carbon Emission Data
Natural stone	160–350	Quarrying: ~50-100 kg CO ₂ /ton of stone.
		Processing: ~100-200 kg CO ₂ /ton of stone. (Energy consumption from cutting, polishing, and other processes)
		Transportation: ~10-50 kg CO ₂ /ton of stone. (Depending on distance, mode, etc.)
Artificial stone	160–400	Raw Material Production: ~50-150 kg CO ₂ /ton of stone.
		Processing: ~100-200 kg CO ₂ /ton of stone.
		Transportation: ~10-50 kg CO ₂ /ton of stone.
Recycled stone	60–130	Processing: ~50-100 kg CO ₂ /ton of stone.
		Transportation: ~10-30 kg CO ₂ /ton of stone.

Based on the above analysis, it can be concluded that integrating clean energy sources into the quarrying and processing stages, improving the utilization efficiency of stone resources, reducing the demand for natural and non-local stone, and optimizing transportation logistics can collectively lead to a significant reduction in the carbon footprint associated with stone usage.

2.3. Wood

In research focused on reducing the carbon footprint of buildings and landscapes, wood offers distinct advantages compared to carbon-intensive materials such as concrete, steel, and stone. The study by Mariusz Hermansdorfer et al. found that using wood and wood products can reduce the Global Warming Potential (GWP) by up to

34% compared to conventional concrete and steel. [3] Wood requires less energy in its processing and production. Relevant studies indicate that processing 1 cubic meter of wood (dimensional lumber) emits only about 30.3 kg of CO₂ equivalent, significantly lower than the carbon emissions from steel (6,470 kg/ton), cement (1,220 kg/ton), and glass (1,870 kg/ton). If fast-growing tree species are used, carbon emissions can be further reduced.

Wood also exhibits a high carbon sequestration capacity. In China, the average carbon storage is approximately 889.328 kg of CO₂ equivalent per cubic meter for logs and sawn timber, and about 1,145.79 kg of CO₂ equivalent for wood-based panels. [4] Consequently, various wood products processed from timber achieve significant carbon sequestration effects. Moreover, the carbon emissions and sequestration capacity vary across different tree species and wood materials.

2.4. Metal

Metallic materials are gaining increasing attention and application in landscape design due to their notable advantages, including high strength, durability, and recyclability. The carbon emissions associated with metallic materials are primarily concentrated in the production stage. Through technological innovation and process optimization, significant reductions in carbon emissions can be achieved during this phase. Carbon emissions from transportation vary depending on the mode and distance, yet generally constitute a smaller portion compared to those from production. These can be minimized by opting for low-carbon transportation modes, reducing transport distances, and optimizing loading methods. Carbon emission data for common metallic materials during the production stage are presented in Table 3.

Table 3. CO₂ Emissions of Various Metallic Materials.

Metal Types	Carbon Emission Range (kg CO ₂ /ton)	Emission Reduction Potential
Ordinary Steel	1.95-3.05	Low (Process optimization + Energy transformation)
Recycled Steel	0.48	Medium (Cost-effective)
Primary Stainless Steel (Nickel-Based)	4.0~6.0 (The Nickel Pig Iron (NPI) process accounts for a substantial share of production.)	Medium (Scrap proportion + Process optimization + Energy structure adjustment)
Recycled Stainless Steel	0.4-0.6	High (Long lifespan + Maintenance-free)
Primary Aluminum	8.5~11.7	Low (Rely on energy transformation)
Recycled Aluminum	0.2-0.5	Very High (Lightweight + 90% recyclability)
Weathering Steel	2.1	Medium (No paint required)

With the advancement of low-carbon technologies, alternative materials to metals have emerged. For instance, nano poly-carbon composite materials—a type of low-carbon metal-mimicking material—have been widely adopted due to their advantageous characteristics such as low carbon emissions, light weight, corrosion resistance, and UV stability. However, they also present challenges in terms of recyclability.

2.5. Glass

In landscape design, glass is widely used in energy-efficient buildings due to its thermal insulation properties. For example, the application of insulating glass can reduce a building's electricity consumption, though it does not directly lower the carbon emissions of the landscape material itself. However, glass manufacturing is a typical energy-intensive industry. The production process requires high-temperature calcination, leading to significant CO₂ emissions. The carbon emissions during the glass production stage are approximately 0.8–1.2 tons of CO₂ per ton of glass (depending on fuel type and process efficiency). Although glass is theoretically capable of low-carbon production and infinite recycling, the actual recycling rate remains far below the theoretical value, resulting in resource waste and increased carbon emissions. According to research data, in 2023, approximately 11 million tons of waste glass were recycled in China, with a recycling rate of only about 25% (compared to around 74% in the EU). Over 70% of waste glass ends up in landfills or is discarded.

Therefore, in low-carbon landscape design, the use of glass should be minimized wherever possible. Concurrently, technological innovation and policy guidance should be leveraged to enhance the recycling rate of glass materials and to explore superior low-carbon alternatives.

2.6. Other Materials (Plastics, Coatings)

Plastic landscape materials primarily include wood-plastic composites (WPC), recycled plastic paving materials, and 3D-printed landscape components. Their carbon emissions are predominantly generated during the raw material production and processing/manufacturing stages. Additionally, while plastic materials have a low density, their large volume requires special consideration regarding transportation-related emissions. Currently, the plastics used are mainly virgin plastic, recycled plastic, and bio-based plastic. (As shown in Table 4)

Table 4. CO₂ Emissions of Various Plastic Materials.

Material Types	Carbon Emission Range (kg CO ₂ /ton)	Key Emission Stages	Implementation Challenges
Virgin Plastic	3.0-4.5	Raw material extraction + Polymerization	Low recycling rate
Recycled Plastic	0.8-1.5	Waste Sorting + Reprocessing	Stringent Requirements for performance stability
Bio-based Plastic	1.5-3.0	Crop cultivation + Transformation	High cost

Therefore, selecting plastics for low-carbon landscapes should prioritize composites with recycled content and the adoption of bio-based plastics. To minimize the carbon footprint effectively, it is crucial to concurrently optimize production technologies, increase the use of clean energy in manufacturing, and establish a comprehensive recycling system to enhance recycling rates.

Coatings are widely used in landscape engineering for applications such as anti-corrosion, decoration, and signage. However, their production, transportation, and application processes involve significant carbon emissions. To mitigate environmental impact, the coatings industry is accelerating its transition toward low-carbon technologies such as water-based coatings, high-solid coatings, and bio-based resins. Among these, water-based coatings can reduce carbon emissions by 30% to 50% compared to traditional solvent-based coatings, while renewable materials like bio-

based epoxy resins can reduce the carbon footprint by over 40%. Furthermore, photocatalytic and self-cleaning coatings indirectly reduce long-term carbon emissions by extending maintenance cycles. In the future, through measures such as the adoption of low-carbon raw materials, intelligent application technologies, and industry consolidation, the carbon footprint of coatings in landscape applications is expected to be further reduced.

3. Selection of Low-Carbon Landscape Materials

Low-carbon landscape materials play a crucial role in advancing eco-friendly development, yet their practical application faces multiple limitations. These include cost constraints, performance and durability concerns, technological barriers, market availability issues, and challenges in maintenance and recycling. Therefore, material selection must be guided by comprehensive life cycle assessment, context-specific optimization, and tailored solutions based on local conditions.

3.1. Prioritize the Use of Local Materials

The use of local materials should be the primary principle in low-carbon landscape construction. Its core advantage lies in significantly reducing the “transportation carbon footprint.” Long-distance transportation relies on fossil fuels and generates substantial CO₂ emissions, whereas sourcing materials locally can fundamentally reduce this hidden carbon cost. Furthermore, local materials are often highly compatible with the regional natural environment, historical context, and architectural style, naturally creating a distinctive landscape character and avoiding the homogenization of “generic cityscapes.” For example, using laterite bricks and granite in Fujian, or blue bricks, tiles, and Taihu Lake stones in the Jiangnan watertowns, not only reduces costs but also perpetuates and strengthens regional cultural identity. Simultaneously, the extraction, processing, and supply chains for local materials are relatively mature and stable, contributing to the support of local economic development.

3.2. Rational Utilization of Natural Organic Materials

Natural organic materials consume significantly less energy during production and processing compared to synthetic materials such as steel, cement, and plastics, resulting in substantially lower carbon emissions. Their most notable characteristic is biodegradability, allowing them to return to nature at the end of their life cycle, closing the material loop with minimal solid waste generation and significantly reducing the environmental burden.

Furthermore, natural materials such as wood and bamboo act as carbon reservoirs. Through photosynthesis during growth, they sequester atmospheric carbon dioxide, storing it in solid form within landscape structures for extended periods and thereby serving as an effective carbon sink. However, the carbon sequestration capacity of wood varies significantly due to differences in tree age, growth environment, and species. Therefore, the rational selection of wood types can maximize carbon sequestration benefits. [5] From an aesthetic perspective, the use of natural materials in landscape architecture can impart warm textures, a natural atmosphere, and time-varying colors to the space, enhancing its affinity and ecological aesthetic. However, it is essential to weigh their durability and maintenance requirements against the specific application context.

3.3. Vigorously Develo Rrecycled Materials

Circular materials refer to waste or non-degradable materials that are recycled, processed, and reused in landscape construction. Their application is a key measure in practicing the circular economy principle of “turning waste into valuable resources.” The production of recycled materials consumes far less energy and generates significantly lower carbon emissions than extracting virgin resources and manufacturing new products, resulting in dual savings in energy and carbon output. This practice demonstrates not only prudent resource stewardship but also respect for the natural environment. Successful applications include rubber paving from waste tires, landscape platforms from reclaimed timber, and crushed demolition concrete as a sub-base layer. Promoting these materials helps accelerate society's transition toward a “resource-product-renewed resource” closed-loop model.

3.4. Promote Permeable Paving Materials

The sponge city concept not only effectively manages rainwater resources but also demonstrates remarkable ecological carbon sequestration capabilities. Through high-density vegetation configuration and a healthy soil environment, it achieves extremely high carbon sink efficiency, with a carbon sequestration capacity per unit area up to five times that of a tropical rainforest. Permeable paving is a crucial material for sponge city construction. By reestablishing the surface hydrological cycle, it effectively replenishes groundwater resources and mitigates the decline of urban groundwater levels. During heavy rainfall, it significantly reduces the velocity and volume of surface runoff, alleviating pressure on municipal drainage systems and reducing the risk of waterlogging. The process of rainwater infiltration also serves as a natural filtration and purification mechanism, mitigating non-point source pollution (such as oils and heavy metals) carried by runoff. Furthermore, permeable paving creates a microclimatic effect by regulating surface temperature and humidity; in summer, moisture evaporation absorbs heat, effectively mitigating the urban heat island effect and improving pedestrian thermal comfort. Selecting permeable paving is an excellent strategy for integrating ecological functions, practicality, and aesthetics in landscape infrastructure.

3.5. Scientifically Select New Materials

The application of new materials represents the cutting-edge direction and future potential of low-carbon landscape development. These materials often leverage technological breakthroughs to achieve low-carbon or even carbon-negative impacts at the source. For instance, low-carbon cement, utilizing improved formulations or alternative cementitious materials, can reduce carbon emissions by up to 30%-50% compared to traditional cement production. Photocatalytic coatings can break down air pollutants like nitrogen oxides under light exposure, providing paving and wall surfaces with the ecological function of actively purifying air. Bio-based composite materials (e.g., combining rice husks, straw with resins) enable the resource utilization of agricultural waste. The adoption of these new materials requires decision-makers to possess a forward-looking vision and thoroughly understand their performance, long-term durability, and local adaptability. Through careful validation via pilot projects, they can steer the landscape industry toward a sustainable future characterized by high technology, high performance, and low environmental impact.

4. Conclusions

The rational selection and ecological design of hardscape materials play a vital role in achieving China's "Dual Carbon" goals. A comprehensive carbon footprint assessment across the entire lifecycle—from material sourcing and production to construction, use, and end-of-life recycling—is essential. Moreover, material selection must be scientifically tailored to practical engineering needs and regional characteristics. Looking forward, the landscape architecture industry must intensify the research, development, and application of low-carbon materials, refine carbon benefit assessment systems, and foster interdisciplinary technological integration. These efforts are crucial for building sustainable landscape systems that are low-carbon, efficient, and aesthetically pleasing, thereby providing industry support and practical pathways for the national "Dual Carbon" strategy.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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