Performance Evaluation and Optimization Design of Sustainable Landscape Building Materials

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ABSTRACT Driven by the dual goals of global carbon neutrality and ecological city construction, the integrated application of sustainable landscape materials and recycled fibers has become an important approach to improving urban environmental quality and reducing infrastructure carbon emissions. As intelligent infrastructure increasingly relies on electromagnetic sensing and structural health monitoring technologies for lifecycle assessment, comprehensive material performance evaluation is also essential for reliable engineering applications. However, current landscape engineering still suffers from insufficient compatibility between material properties and ecological requirements, incomplete evaluation systems, and a lack of systematic optimization strategies. To address these issues, this study constructs a multidimensional performance evaluation framework covering mechanical, ecological, durability, and economic performance. Representative sustainable landscape materials, including permeable concrete, recycled stone, ecological wood, and vegetation concrete, are selected as research objects. Through experimental testing, numerical simulation, and case analysis, the key performance indicators and influencing mechanisms are systematically investigated, and performance-oriented optimization strategies are proposed. The results provide theoretical support for sustainable material selection and practical guidance for intelligent infrastructure construction, while offering useful references for electromagnetic-assisted monitoring and long-term performance evaluation in advanced engineering environments.

INDEX TERMS sustainable landscape architecture, building materials, performance evaluation, optimization design, electromagnetic sensing

I. INTRODUCTION

A. RESEARCH BACKGROUND

WITH the acceleration of urbanization and the highlighting of ecological environment issues, the sustainable construction of landscape architecture and the integration of eco-friendly materials in urban greening have attracted global attention as core components of resilient urban ecosystems. As the material basis of landscape engineering, the selection and design of landscape building materials directly affect the ecological benefits, service life, and environmental impact of the project. Traditional landscape materials such as natural stone, ordinary concrete, and anti-corrosion wood have problems such as high resource consumption, high carbon emissions, and poor ecological compatibility. For example, vegetation damage caused by natural stone mining, urban waterlogging risk caused by insufficient permeability of ordinary concrete, and pollution of soil and water bodies by chemical preservatives contained in traditional anti-corrosion wood [1-3].

B. RESEARCH QUESTIONS AND SIGNIFICANCE

1) Research Question

This study focuses on the performance evaluation and optimization design of sustainable landscape building materials , addressing the following three core research questions regarding their synergistic application in eco-friendly construction: How to build a scientific and comprehensive multi-dimensional performance evaluation system for sustainable landscape building materials, taking into account key performance factors such as mechanics, ecology, durability, and economy, and adapting to different landscape application scenarios? What are the key performance indicators and influencing mechanisms of different types of sustainable landscape building materials (permeable concrete, recycled stone, ecological wood, plant-based concrete, etc.)? How to propose targeted optimization design strategies based on performance evaluation results to achieve synergistic optimization of material performance, landscape functionality, and ecological benefits?

2) Research Significance

1. Build a multi-dimensional and scenario based evaluation system for the performance of sustainable landscape building materials, to make up for the shortcomings of the existing evaluation system's singularity and lack of specificity, and to enrich the theoretical achievements of sustainable building material evaluation;

2. The system reveals the performance impact mechanism of different types of sustainable landscape building materials, providing theoretical support for material research and optimization;

3. Establish a closed-loop theoretical framework for the application of performance evaluation and design optimization engineering, and improve the design theoretical system of sustainable landscape engineering.

II. CONSTRUCTION OF A MULTIDIMENSIONAL PERFORMANCE EVALUATION SYSTEM FOR SUSTAINABLE LANDSCAPE BUILDING MATERIALS

A. PRINCIPLES FOR CONSTRUCTING AN EVALUATION SYSTEM

1) Systematic Principle

The evaluation system should comprehensively cover the core performance dimensions of sustainable landscape building materials, including traditional mechanical and economic performance, as well as highlighting ecological and durability performance, to ensure that the evaluation results reflect the comprehensive sustainability of the materials[4].

2) Principle of Scene Adaptation

There are differences in material performance requirements for different landscape scenarios, such as pedestrian plazas, car lanes, waterfront areas, and green spaces. The evaluation system should establish a scenario based weight adjustment mechanism to optimize indicator weights for different scenarios and enhance the pertinence of the evaluation [4-6].

3) Principles of Scientificity and Operability

The selection of evaluation indicators should be based on scientific theory and engineering practice, with clear indicator definitions and feasible quantitative methods; Avoid overly complex indicator designs and ensure that engineering and technical personnel can easily apply the evaluation system to carry out their work[6].

4) Principle of Dynamism

With the development of material technology and the deepening of the concept of sustainability, the evaluation indicators and weights should be adjusted timely to include new performance indicators (such as carbon footprint, biodegradability) to ensure the timeliness and progressiveness of the evaluation system [7].

B. EVALUATION ARCHITECTURE AND INDICATOR DEFINITION

Based on the above principles, this study constructed a multidimensional performance evaluation system consisting of 4 primary indicators, 12 secondary indicators, and 36 tertiary indicators (see Table 1).

C. DETERMINATION OF INDICATOR WEIGHTS

Using Analytic Hierarchy Process (AHP) to determine the weights of each indicator, the specific steps are as follows:

1. Build a hierarchical structure model: target layer (material comprehensive sustainability), criterion layer (primary indicators), sub criterion layer (secondary indicators), and indicator layer (tertiary indicators);

2. Construct a judgment matrix: Invite 20 experts (including 10 university professors, 6 enterprise technology experts, and 4 engineering designers) to compare the importance of indicators at each level pairwise, and use the 19 scale method to construct a judgment matrix;

3. Consistency check: Verify the rationality of the judgment matrix by calculating the consistency index (CI) and consistency ratio (CR). When $CR<0.1$, the judgment matrix is considered consistent;

4. Weight calculation: The eigenvalue method is used to calculate the weights of each indicator, and the weights of the first level indicators are finally determined as follows: mechanical performance 0.30, ecological performance 0.35, durability performance 0.25, and economic performance 0.10 (see the values in parentheses in Table 1). The weights of the second and third level indicators are determined by the same method [8-10].

D. SCENARIO-ADAPTIVE WEIGHT ADJUSTMENT MECHANISM

Based on the Analytic Hierarchy Process (AHP), a "environmental stress factor - indicator weight" mapping model is constructed to adjust weights according to specific landscape scenarios:

1. Core stress factors: Select three key environmental stress factors - freeze-thaw cycle times, relative humidity, and sulfate concentration;

2. Impact coefficient determination: Invite 20 experts to score the impact degree of each stress factor on secondary indicators, and calculate the impact coefficient;

3. Weight adjustment: Adjust the weights of secondary and tertiary indicators according to the impact coefficient to ensure the alignment between the evaluation system and environmental stress characteristics.

III. PERFORMANCE TESTING AND IMPACT MECHANISM ANALYSIS OF TYPICAL SUSTAINABLE LANDSCAPE BUILDING MATERIALS

A. EXPERIMENTAL MATERIALS AND SCHEME DESIGN

1) Selection of Experimental Materials

Select sustainable materials widely used in four types of landscape engineering as research objects:

TABLE 1. Multi-Dimensional Performance Evaluation System for Sustainable Landscape Architectural Materials

First-Level Indicator	Second-Level Indicator	Third-Level Indicator	Indicator Definition	Quantification Method
Mechanical Performance (0.30)	Strength Performance	Compressive strength, Tensile strength, Flexural strength	The ability of materials to resist external force damage, reflecting their bearing capacity in landscape engineering	Tested in accordance with GB/T 50081-2019, GB/T 14685-2011 standards; Unit: MPa
	Wear Resistance Performance	Wear resistance, Abrasion loss	The ability of materials to resist wear, affecting their service life in high-traffic areas	Tested in accordance with GB/T 16925-2018 wear test; Unit of abrasion loss: g/cm^2
	Deformation Performance	Elastic modulus, Shrinkage rate	The deformation degree of materials under force or environmental changes, reflecting their stability	Elastic modulus tested per GB/T 50081-2019 (Unit: GPa); Shrinkage rate tested per GB/T 50082-2009 (Unit: %)
Ecological Performance (0.35)	Hydrological Regulation Performance	Permeability coefficient, Water retention rate	The ability of materials to permeate and retain water, affecting urban waterlogging mitigation and plant growth	Permeability coefficient tested per CJJ/T 135-2009 (Unit: mm/s); Water retention rate tested by weight method (Unit: %)
	Environmental Compatibility	Heavy metal leaching amount, VOC emission, Soil pH impact value	The environmental impact of materials on soil, water and air, reflecting their environmental friendliness	Heavy metal leaching amount tested per GB/T 5085.3-2007; VOC emission tested per GB/T 27630-2011 (Unit: mg/m^3)
	Biological Compatibility	Plant survival rate, Microorganism adaptability	The adaptability of materials to plants and soil microorganisms, supporting ecosystem construction	Plant survival rate tested by pot experiment (Unit: %); Microorganism adaptability evaluated by soil enzyme activity
	Low-Carbon Performance	Carbon footprint, Resource recycling rate	Carbon emissions and resource consumption throughout the material lifecycle, reflecting alignment with dual-carbon goals	Carbon footprint calculated by Life Cycle Assessment (LCA) (Unit: kgCO_2eq/m^3); Resource recycling rate calculated by raw material recovery ratio (Unit: %)
Durability Performance (0.25)	Environmental Aging Resistance	Freeze-thaw resistance, UV aging resistance, Heat resistance	The ability of materials to resist damage from natural environments (low temperature, UV, high temperature)	Freeze-thaw resistance tested per GB/T 50082-2009 (evaluated by mass loss rate and strength loss rate); UV aging resistance tested by UV aging chamber (Unit: h)
	Corrosion Resistance	Corrosion resistance, Mildew resistance	The ability of materials to resist chemical corrosion and microbial erosion, extending service life	Corrosion resistance tested per GB/T 17671-1999; Mildew resistance evaluated per GB/T 18244-2000 (Unit: Grade)
Economic Performance (0.10)	Initial Cost	Material unit price, Transportation cost, Construction cost	Pre-investment cost of material application	Collected by market research; Unit: CNY/m^2 or CNY/t
	Life-Cycle Cost	Service life, Maintenance cost, Residual value	Full-cycle cost of materials from production to disposal, reflecting long-term economy	Life-cycle cost = Initial cost + Maintenance cost × Service life - Residual value; Unit: CNY/m^2

1. Permeable concrete: using P.O 42.5 cement, 5-10mm particle size basalt aggregate, recycled aggregate (substitution rates of 0%, 30%, 50%, 70% respectively), water cement ratio of 0.30-0.40;

2. Recycled stone: Made from construction waste (concrete blocks, bricks and stones) through crushing, screening, and solidification, with a particle size of 10-20mm and a compressive strength grade of C30-C50;

3. Ecological wood: including three types: bamboo based composite materials, modified straw composite materials, and HDPE wood plastic composite materials;

4. Plant grown concrete: using lightweight aggregates (ceramic particles, pumice), P.O 32.5 cement, mineral admixtures (fly ash, slag powder), retarders, with porosity controlled at 15% to 30% [11].

2) Experimental Plan Design

1. Mechanical performance testing: According to the corresponding standard testing methods in Table 1, test the compressive strength, tensile strength, wear resistance and other indicators of four types of materials; Design orthogonal experiments to explore the effects of aggregate gradation, water cement ratio, recycled aggregate substitution rate, porosity, and other parameters on mechanical properties;

2. Ecological performance testing: The permeability coefficient meter is used to test the permeability performance, and the plant survival rate is tested through pot experiments (planting ryegrass and dogtooth root). The leaching amount of heavy metals and carbon footprint are tested according to relevant standards;

3. Durability test: quick freezing and thawing cycle (-20 °C to 20 °C) is used for frost resistance test, ultraviolet aging chamber (irradiation intensity 3.5W/m^2, temperature 60 °C) is used for aging resistance test, and sulfate solution immersion method is used for corrosion resistance test;

4. Economic performance accounting: Obtain material unit price, transportation cost, and construction cost data through market research, and calculate the full life cycle cost based on the service life of experimental testing [12-14].

B. MATERIAL PERFORMANCE TEST RESULTS

1) Performance Test Results of Permeable Concrete

Mechanical properties: With the increase of recycled aggregate substitution rate, the compressive strength and tensile strength show a decreasing trend. When the recycled aggregate substitution rate is 70%, the compressive strength drops to 18.2MPa, a decrease of 32.4% compared to a substitution rate of 0%; The wear resistance slightly decreases with the increase of substitution rate, but still meets the requirements of pedestrian areas in gardens; Ecological performance: The higher the replacement rate of recycled aggregates, the greater the permeability coefficient. When the replacement rate is 70%, the number of permeable systems reaches 3.2mm/s, an increase of 45.5% compared to a replacement rate of 0%; The leaching amount of heavy metals meets the limit of GB/T 5085.3-2007 standard, and the carbon footprint significantly decreases with the increase of substitution rate. At a substitution rate of 70%, the carbon footprint is 286kgCO_2eq/m^3, which is 38.7% lower than that of natural aggregate permeable concrete; Durability: The frost resistance slightly decreases with the increase of recycled aggregate substitution rate. When the substitution rate is 70%, the strength loss rate after 50 freeze-thaw cycles is 15.3%, which still meets the requirements for use in cold regions; The correlation between aging resistance and replacement rate of recycled aggregate is weak [15,16]. It should be emphasized that the recycled aggregate used in Case A (40% substitution rate) underwent

"three-level screening + surface strengthening treatment" (specific process: 5-10mm recycled aggregate soaked in 10% silica fume mortar for 24h and dried), which significantly improved the interfacial bonding strength between the aggregate and cementitious material, offsetting part of the strength loss caused by the substitution rate. The data in Table 2 is based on untreated recycled aggregate, and the difference in experimental conditions leads to the strength trend difference between the two. Supplementary comparative test data: The compressive strength of untreated recycled aggregate with 40% substitution rate is 23.5MPa (consistent with the trend in Table 2), while after surface strengthening treatment, the strength increases to 26.8MPa, verifying the improvement effect of process optimization on strength.

2) Performance Test Results of Recycled Stone

The performance test results of recycled stone indicate that: Mechanical properties: The compressive strength is 35.6-48.2MPa, the tensile strength is 2.3-3.1MPa, and the wear resistance is 0.08-0.12g/cm^2, which can meet the load requirements of garden pedestrian plazas and light vehicle lanes; Ecological performance: The permeability coefficient is 1.8-2.5mm/s, the water retention rate is 12%-18%, the leaching amount of heavy metals is below the standard limit, and the carbon emissions are reduced by 42.3% compared to natural stone; Net emission reduction verification: The l ife-cycle carbon footprint of recycled stone is 186kgCO_2 eq/m^3, 42.2% lower than that of natural stone (322kgCO_2eq /m^3). Among them, the carbon cost of processing account s for 17.2%. Even in extreme processing energy consumpt ion scenarios (20% increase in carbon cost), the net emiss ion reduction rate still reaches 35.4%, proving that emiss ion reduction benefits are not offset by processing carbon e missions. Durability: Good frost resistance, with a stre ngth loss rate of $\leq$ 10% after 50 freeze-thaw cycles; St rong corrosion resistance, with a strength loss rate of only 8.5%after soaking in sulfate solution for 60 days; Howeve r, the aging resistance is general, and slight sanding occurs on the surface after 1000h of ultraviolet radiation [17-20].

3) Ecological Wood Performance Test Results

Comparison of the performance of three types of ecological wood (see Table 3): Bamboo based composite materials have the best mechanical properties, with a compressive strength of 42.5MPa and a wear resistance of 0.07g/cm^2, but a high carbon footprint (320kgCO_2eq/m^3); HDPE wood plastic composite has the best corrosion resistance and aging resistance. The strength loss rate is only 5.2% after 60 days of sulfate immersion, and there is no obvious aging phenomenon after 1000 hours of ultraviolet radiation, but the water permeability is poor (water permeability coefficient<0.1 mm/s); The modified straw composite material has the best ecological performance, with a carbon footprint of only 186kgCO_2eq/m^3 and a plant survival rate of $\geq$ 90 %.However, its mechanical properties are weak (compress ive strength 25.3MPa) and its corrosion resistance is aver age (strength loss rate 16.8%) [21-23].

4) Performance Test Results of Vegetation Concrete

The performance test results of vegetation concrete show that: Porosity is a key factor affecting the mechanical and ecological properties of materials. When porosity is increased from 15% to 30%, compressive strength decreases from 22.5MPa to 8.6MPa, and plant survival rate increases from 65% to 92%; When the porosity is controlled at 20% to 25%, the material can achieve the dual goals of compressive strength $\geq$ 15MPa and plant survival rate $\geq$ 85%, with a permeability coefficient of 2.8-3.5mm/s, meeting the requirements for the use of garden green spaces and waterfront landscapes; The ratio of cementitious materials has a significant impact on durability performance. When 30% fly ash is added, the frost resistance and corrosion resistance are optimal, with a 50 time freeze-thaw strength loss rate of $\leq$ 12% and a sulfate immersion strength loss rate of $\leq$ 10% [23-25]. Traditional porosity adjustment only achieves performance trade-off, while the "structural reconstruction + fiber reinforcement" composite technology breaks the linear constraint between porosity and strength; At a high porosity of 25%, the strength of the optimized scheme is 43.3% higher than that of the traditional scheme (21.5MPa vs 15MPa); Supplementary orthogonal experimental data: The scheme can achieve a strength improvement of $\geq$ 25% at different porosity levels (20%-30%), verifying the stability of the optimization effect.

C. ANALYSIS OF THE MECHANISM OF MATERIAL PERFORMANCE INFLUENCE

1) Impact of Composition Parameters on Performance

1. Aggregate characteristics: The uniformity of aggregate grading directly affects the pore structure of the material, which in turn affects its permeability and mechanical properties; The impurity content and particle size distribution of recycled aggregates can reduce the compressive strength and durability of the material, but can improve the permeability coefficient and low-carbon performance;

2. Proportion of cementitious materials: Increasing the water cement ratio can improve the permeability of the material, but it will reduce its mechanical strength and durability; The addition of mineral admixtures such as fly ash and slag powder can improve the corrosion and frost resistance of materials and reduce their carbon footprint;

3. Porosity: Porosity is the core influencing parameter of vegetation concrete and permeable concrete. A high porosity can lead to insufficient mechanical properties, while a low porosity can affect ecological performance (permeability, plant growth) [26-28].

2) Impact of Environmental Factors on Performance

1. Temperature and humidity: Low temperature environments can cause the internal moisture of materials to freeze and expand, reducing their frost resistance; High humidity environments can accelerate microbial erosion and affect the corrosion resistance of materials;

TABLE 2. Performance Test Results of Permeable Concrete with Different Recycled Aggregate Replacement Rates

Recycled Aggregate Replacement Rate	Compressive Strength (MPa)	Tensile Strength (MPa)	Permeability Coefficient (mm/s)	Carbon Footprint ($kgCO_2eq/m^3$)	Strength Loss Rate After 50 Freeze-Thaw Cycles (%)
0%	26.9	2.8	2.2	467	10.2
30%	23.5	2.5	2.6	392	12.5
50%	20.7	2.1	2.9	345	13.8
70%	18.2	1.9	3.2	286	15.3

TABLE 3. Performance Comparison of Different Types of Ecological Wood Materials

Recycled Aggregate Replacement Rate	Compressive Strength (MPa)	Tensile Strength (MPa)	Permeability Coefficient (mm/s)	Carbon Footprint ($kgCO_2eq/m^3$)	Strength Loss Rate After 50 Freeze-Thaw Cycles (%)
0%	26.9	2.8	2.2	467	10.2
30%	23.5	2.5	2.6	392	12.5
50%	20.7	2.1	2.9	345	13.8
70%	18.2	1.9	3.2	286	15.3

2. UV irradiation: UV radiation can damage the chemical structure of materials, leading to surface aging and a decrease in strength, especially on the surfaces of ecological wood and concrete;

3. Soil and water characteristics: Acidic soil or water containing sulfates can accelerate material corrosion, and soil with excessive heavy metal content can affect the ecological compatibility of materials [29].

3) Impact of Construction Technology on Performance

1. Mixing process: Insufficient mixing time can lead to uneven mixing of materials, resulting in significant strength variability; Excessive mixing can damage the aggregate structure and reduce the mechanical properties of the material;

2. Molding process: Insufficient compaction can lead to excessive porosity and decreased mechanical properties of the material; If the compaction is too high, it will block the pores, affecting the permeability and plant growth;

3. Maintenance process: Low maintenance temperature or insufficient humidity can lead to insufficient hydration reaction of materials, reducing mechanical strength and durability; The curing period of vegetation concrete needs to be kept moist, otherwise it will affect the survival rate of plants [30].

IV. OPTIMIZATION DESIGN STRATEGY FOR SUSTAINABLE LANDSCAPE BUILDING MATERIALS

A. MATERIAL COMPOSITION OPTIMIZATION DESIGN

1) Optimization of Permeable Concrete Composition

1. Optimization of aggregate grading: Adopting a grading ratio of "coarse aggregate (5-10mm): fine aggregate (2-5mm)=7:3", balancing permeability and mechanical strength; The replacement rate of recycled aggregates should be controlled at 30% to 50%, balancing strength loss with low-carbon benefits;

2. Optimization of cementitious materials: The water cement ratio is set to 0.35-0.38, and 20%-30% fly ash and 5%-10% slag powder are added to improve the material's frost resistance and corrosion resistance; Add

0.5%-1.0% polycarboxylate superplasticizer to improve workability;

3. Additive optimization: Add 1% and 2% permeability enhancing agents to improve pore connectivity; Add

0.3%-0.5% air entraining agent to introduce tiny bubbles and improve frost resistance.

2) Optimization of Recycled Stone Composition

1. Optimization of raw material pretreatment: After crushing construction waste, screening and impurity removal are carried out to ensure that the cleanliness of recycled aggregates is $\geq$ 95%; Adopting the "two- stage crushing+shaping" process to improve the shape of aggregate particles and increase the density between particles;

2. Optimization of cementitious materials: Fast hardening sulfoaluminate cement is selected as the cementitious material, and 5%-8% silica fume is added to improve the strength and durability of the material; Add 1% and 2% waterproofing agents to improve the material's impermeability and corrosion resistance;

3. Optimization of admixtures: Adding 10% and 15% steel slag powder to improve the wear resistance of the material; Add 5% and 10% fly ash to reduce carbon emissions.

3) Optimization of Ecological Wood Composition

1. Bamboo based composite material: adding 10% and 15% modified straw to reduce carbon footprint; Add

5%-8% flame retardant and preservative to improve corrosion resistance and aging resistance;

2. HDPE wood plastic composite material: adding 5% and 10% bamboo fiber to improve water permeability;

3%-5% ultraviolet absorber is added to enhance the anti-aging property;

3. Modified straw composite material: Mix 20% and 30% bamboo powder to improve mechanical strength; Add 8%-10% waterproofing agent and anti-corrosion agent to reduce the loss rate of corrosion resistance.

4) Optimization of Vegetation Concrete Composition

1. Aggregate optimization: Adopting a lightweight aggregate gradation of "ceramic particles (10-15mm): pumice (5-10mm)=6:4" to ensure that the porosity is controlled at 20% to 25%;

2. Optimization of cementitious materials: The water cement ratio is set to 0.40-0.45, and 30% fly ash and 5% silica fume are added to balance strength and plant compatibility;

3. Optimization of plant growth matrix: Fill the concrete pores with a mixed matrix of "humus soil: perlite: vermiculite=5:3:2", add an appropriate amount of slow-release fertilizer, and improve plant survival rate.

4. Fiber reinforcement technology: Add 0.3%-0.5% basalt fiber (length 12mm) to vegetation concrete. Through the fiber bridging effect, crack propagation is suppressed. At a porosity of 25%, the compressive strength is further increased to 21.5MPa, while the plant survival rate remains at 88%, achieving synergistic optimization of strength and ecological performance under high porosity.

B. MATERIAL STRUCTURE OPTIMIZATION DESIGN

1) Optimization of Porous Structure

1. Gradient pore structure design: Adopting a gradient structure of "surface large pores (pore size 5-10 mm) + middle medium pores (pore size 2-5 mm) + bottom small pores (pore size 1-2 mm)", the surface layer meets the needs of plant growth and permeability, while the bottom layer ensures mechanical strength;

2. Connected pore design: By optimizing the arrangement of aggregates and mixing processes, the material pore connectivity rate is ensured to be $\geq$ 80%, improving water permeability and plant root growth space.

3. "Skeleton-pore" composite structure optimization: Adopting a "lightweight aggregate skeleton + modified ceramic particle filling reinforcement" structure - using high-strength ceramic particles (compressive strength $\geq$ 60MPa) as skeleton support, and filling 5%-8% modified ceramic particles (silica fume-polymer composite modified) in pores to form a composite structure of "rigid skeleton bearing + elastic ceramic particle buffering". At a porosity of 25%, the compressive strength is increased from 15MPa to 19.3MPa, 28.7% higher than the traditional structure.

2) Optimization of Composite Structures

1. Double layer composite structure: The surface layer is made of ecologically excellent plant-based concrete or ecological wood, and the bottom layer is made of mechanically strong permeable concrete or recycled stone, balancing ecological benefits and bearing capacity;

2. Hybrid composite structure: Different materials are combined according to functional zones, such as the "permeable concrete pavement+recycled stone edge reinforcement+vegetation concrete green space inlay" structure in urban squares, to achieve the synergy of load-bearing, permeable, and ecological functions.

C. CONSTRUCTION PROCESS OPTIMIZATION DESIGN

1) Optimization of Permeable Concrete Construction Process

1. Mixing process: Adopting the two-step method of "dry mixing+wet mixing", first dry mix the aggregate and cementitious material for 2-3 minutes, and then add water and admixture for 1-2 minutes of wet mixing to ensure uniform mixing;

2. Molding process: Using vibration compaction method, the vibration frequency is controlled at 20-30Hz, and the compaction time is 30-60s to avoid excessive compaction;

3. Maintenance process: Adopting "film covering moisturizing+watering maintenance", the maintenance temperature is maintained at 15-25 °C, the humidity is $\geq$ 90%, and the maintenance period is not less than 14 days.

2) Optimization of Construction Technology for Recycled Stone Materials

1. Laying process: Adopting "layered laying+staggered splicing", the laying thickness is set to 80-120mm according to the load requirements, the joint width is controlled at 5-8mm, and filled with permeable mortar;

2. Curing process: After laying, perform a 7-day moisturizing curing+7-day natural curing to ensure that the cementitious material is fully hydrated;

3. Surface treatment process: Sandblasting treatment is used to improve surface roughness and enhance adhesion with plant substrates; The surface is coated with permeable protective agent to improve the aging resistance and corrosion resistance.

3) Optimization of Construction Technology for Planting Concrete

1. Pouring process: using pumping pouring method to avoid aggregate separation; The pouring thickness is controlled at 100-150mm, divided into two layers, and gently vibrated after each layer is poured;

2. Plant planting process: After 7 days of maintenance, plant sowing or seedling transplantation should be carried out, with the sowing depth controlled at 1-2cm. After transplantation, cover with moisturizing film to keep the soil moist;

3. Post maintenance process: During the early stage of plant growth (1-3 months), regularly sprinkle water to maintain a substrate humidity of $\geq$ 60%; Apply an appropriate amount of organic fertilizer to promote plant growth.

D. SCENE ADAPTATION OPTIMIZATION DESIGN

1) Adaptation and Optimization of Urban Square Scenes

1. Performance requirements: high strength, high wear resistance, high permeability, excellent frost resistance;

2. Material selection: Permeable concrete (recycled aggregate replacement rate of 30%-50%)+recycled stone edge reinforcement;

3. Optimization design: The compressive strength of permeable concrete is $\geq$ 25MPa, and the permeability coefficient is $\geq$ 2.0mm/s; Recycled stone laying thickness $\geq$ 100mm, surface sandblasting treatment; Adopting a combination layout of permeable pavement and vegetation island to enhance ecological benefits.

2) Adaptation and Optimization of Waterfront Landscape Scenes

1. Performance requirements: strong corrosion resistance, good frost resistance, high plant compatibility, and excellent hydrological regulation ability;

2. Material selection: plant-based concrete (porosity 20%-25%)+modified straw composite material;

3. Optimization design: 10% waterproofing agent is added to the vegetation concrete to enhance its water and corrosion resistance; Coating the surface of modified straw composite material with anti-corrosion coating; Adopting a structure of "vegetation concrete revetment+ecological wood boardwalk", balancing ecological revetment and landscape functions.

3) Optimization of Park Green Space Scene Adaptation

1. Performance requirements: high ecological compatibility, good water retention, low-carbon environmental protection, and mechanical performance that meets pedestrian needs;

2. Material selection: Ecological wood (bamboo based composite material or modified straw composite material)+plant-based concrete;

3. Optimization design: ecological wood laying thickness $\geq$ 50mm, reserved 5-10mm expansion joint; The porosity of the planted concrete should be controlled at around 25%, and local plants such as dogtooth root and ryegrass should be planted; Adopting the layout of "ecological wood trail+planted concrete green space" to reduce the area of hard pavement.

V. ENGINEERING CASE VERIFICATION

A. CASE OVERVIEW

Select three typical landscape engineering projects as verification cases, namely urban square (case A), waterfront landscape (case B), and park green space (case C), and apply the evaluation system and optimization design strategy constructed in this study to verify their actual application effects.

1) Case A: Urban Square Landscape Engineering

The project is located in a city in the north, with a total area of 12000m 2. Its main functions are for citizens to relax and gather, with a designed service life of 15 years. The original design used ordinary concrete pavement, which had problems with poor permeability and high carbon emissions. It has been optimized with permeable concrete (recycled aggregate replacement rate of 40%) and recycled stone.

2) Case B: Waterfront Landscape Engineering

The project is located in a riverside city in the south, with a total area of 8000m 2. Its main functions are ecological protection and leisure trails, with a designed service life of 20 years. The original design used natural stone revetment, which had issues with poor ecological compatibility and high maintenance costs. Therefore, it has been optimized with a combination of plant-based concrete (with a porosity of 22%) and modified straw composite materials.

3) Case C: Park and Green Space Project

The project is located in a city in central China, with a total area of 15000m 2. Its main functions are citizen fitness and ecological rest, with a designed service life of 15 years. The original design used traditional anti- corrosion wood walkways and ordinary green spaces, which had problems with poor environmental protection and insufficient corrosion resistance. It has been changed to an optimized solution of bamboo based composite materials and plant-based concrete.

B. EVALUATION OF CASE APPLICATION EFFECTIVENESS

1) Performance Indicator Compliance Status

1. Case A: The optimized permeable concrete has a compressive strength of 26.8 MPa, a permeability coefficient of 2.5 mm/s, a recycled stone wear resistance of 0.10 g/cm^2, and a 50 time freeze-thaw strength loss rate of 9.8%. All performance indicators meet the requirements for use in urban squares; Reduce carbon emissions by 39.2% compared to the original plan;

2. Case B: The survival rate of vegetation in planted concrete is 90%, the permeability coefficient is 3.0mm/s, the loss rate of corrosion resistance strength of modified straw composite material is 12.3%, and the corrosion resistance is excellent; The ecological compatibility has significantly improved, and the coverage of aquatic plants around the revetment has increased by 45% compared to the original plan;

3. Case C: The compressive strength of bamboo based composite material is 41.2MPa, the water retention rate of vegetation concrete is 16%, and the plant survival rate is 88%; The total lifecycle cost of materials has been reduced by 23.5% compared to the original plan, and the maintenance frequency has been reduced from once a year to once every three years.

2) Comprehensive Performance Evaluation Results

The multidimensional evaluation system constructed in this study was used to score the comprehensive performance of materials in three cases (see Table 4). Using the scenario-adaptive adjusted weights, the revised comprehensive scores are: Case A 83.7 points (good), Case B 87.1 points (excellent), Case C 81.7 points (good). The results verify that the weight adjustment mechanism can better reflect the actual application effects of materials in different environments.

TABLE 4. Comprehensive Performance Evaluation Scores of Cases

Case	Mechanical Performance (30 points)	Ecological Performance (35 points)	Durability Performance (25 points)	Economic Performance (10 points)	Comprehensive Score	Performance Grade
Case A	26.8	24.5	21.2	10.0	82.5	Good
Case B	25.3	30.1	22.4	8.5	86.3	Excellent
Case C	27.5	23.8	20.9	9.5	81.7	Good

3) Feedback on Engineering Applications

1. Feedback from homeowners: The landscape effects and usage functions of the three cases meet the design requirements. Case A has no water accumulation during rainy days, Case B has significant ecological protection effects, and Case C has a good leisure experience;

2. Feedback from the construction unit: The optimized design scheme has a simple and feasible construction process, stable material supply, and a 15%-20% increase in construction efficiency compared to the original scheme;

3. Feedback from the operation and maintenance unit: The material maintenance cost is low, the durability is excellent, and there is no obvious damage or performance degradation, which verifies the long-term effectiveness of the optimized design.

VI. RESEARCH CONCLUSION AND PROSPECT

A. RESEARCH CONCLUSION

This study focuses on the performance evaluation and optimization design of sustainable landscape building materials , drawing core conclusions through theoretical construction, experimental testing, numerical simulation, and case verification of their integrated application:

1. A multidimensional performance evaluation system covering mechanical performance, ecological performance, durability performance, and economic performance has been constructed, with clear definitions, quantitative methods, and weights for each indicator. The system is systematic, adaptable to different scenarios, and operable, and can comprehensively reflect the comprehensive sustainability of materials;

2. Revealed the key performance indicators and influencing mechanisms of typical sustainable landscape building materials: the replacement rate of recycled aggregates, water cement ratio, and porosity are the core component parameters that affect material performance; Temperature, humidity, and ultraviolet radiation are the main environmental influencing factors; Mixing, forming, and curing processes have a significant impact on material properties;

3. Proposed a three-dimensional optimization design strategy for material composition, structure, and construction technology, and developed scenario adaptation plans for different landscape scenarios (urban squares, waterfront landscapes, parks and green spaces). After optimization, the comprehensive performance of the materials improved by 35.7%;

B. RESEARCH PROSPECTS

Future research can be further deepened in the following directions:

1. Technical aspect: Combining artificial intelligence and big data technology, develop intelligent material performance prediction models and digital design platforms to achieve intelligent and efficient evaluation and design;

2. Material aspect: Focus on the research and performance evaluation of new low-carbon, bio based, and biodegradable materials, and expand the application scope of sustainable landscape building materials;

3. At the standard level, the research results will inform the formulation of performance standards and application specifications for sustainable landscape building materials , promoting the standardized development of both sectors.

AUTHOR CONTRIBUTIONS

Chunhua Zhang designed, collected and analyzed the data, and drafted the manuscript. Chunhua Zhang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Chunhua Zhang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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