

Optimal Design of Vegetation Concrete in Slope Reinforcement of Water Conservancy Projects

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Abstract

Slope stability in water conservancy projects was a critical engineering concern, as slope failure could lead to flooding, infrastructure damage, and threats to human life. Traditional reinforcement methods such as concrete pouring and stone masonry had limitations including poor ecological compatibility, high cost, and maintenance difficulties. Vegetation concrete, a composite material combining cement, soil, plant seeds, and additives, offered both structural strength for slope stabilization and ecological benefits through vegetation growth and soil erosion reduction. However, its application in water conservancy slope reinforcement remained in the exploratory stage, with challenges including undefined performance parameters, immature optimization methods, and insufficient systematic research.

This study presented an experimental investigation on the optimal design of vegetation concrete for slope reinforcement in water conservancy projects. The research employed a combined approach of laboratory simulation experiments and on-site case study monitoring at the Nuozhadu Hydropower Station. Laboratory tests included FLAC3D numerical simulation for slope stability analysis under varying slope angles (30°, 45°, 60°) and rainfall intensities (50, 100, 150 mm/24h), durability simulation under dry–wet cycling and temperature fluctuation conditions, and orthogonal experiments for material ratio optimization. On-site monitoring covered slope deformation, vegetation germination rate, and ecological performance over a 12-month period.

The results indicated that vegetation concrete slopes with angles up to 45° maintained good stability under rainfall intensities up to 100 mm/24h, with a safety factor of 1.22. After 60 days of durability simulation, compressive strength retention reached 82.3% and no structural cracking was observed. The optimized material ratio (cement 320 kg/m³, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m³, organic nutrient substrate 12%) achieved a 28-day compressive strength of 3.4 MPa with a vegetation germination rate of 92%. Field monitoring confirmed a vegetation coverage rate of 91% after 12 months with Vegetation

concrete, integrating cement, soil, plant seeds, and additives, offers both structural strength and ecological benefits for slope reinforcement, yet its optimization for water conservancy applications remains insufficiently studied. This research investigated the optimal design of vegetation concrete through FLAC3D numerical simulation, durability testing, orthogonal material ratio optimization, and 12-month field monitoring at the Nuozhadu Hydropower Station. Key findings demonstrated that slopes up to 45° maintained stability under rainfall intensities up to 100 mm/24h (safety factor 1.22), while the optimized mix (cement 320 kg/m³, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m³, organic nutrient substrate 12%) achieved 28-day compressive strength of 3.4 MPa with 92% vegetation germination rate. After 60 days of accelerated durability simulation, compressive strength retention reached 82.3% with no structural cracking. Field monitoring confirmed 91% vegetation coverage after 12 months with maximum surface settlement of 12.3 mm. The strong correlation between laboratory and field results ($R^2 = 0.89$) validated the integrated research methodology, providing practical design guidance for vegetation concrete application in water conservancy slope reinforcement.

Keywords: vegetation concrete; slope reinforcement; water conservancy projects; ecological restoration; durability; FLAC3D simulation

Introduction

Slope stability is critical in water conservancy projects, as slope failure can cause flooding, infrastructure damage, and threats to human safety. Traditional reinforcement methods such as concrete pouring and stone masonry, while widely used, exhibit significant limitations in ecological compatibility and long-term sustainability (Liu & Huang, 2022; Wang & Zhang, 2022). Vegetation concrete has emerged as a promising alternative that integrates engineering strength with ecological restoration by combining cement, aggregate, organic substrate, plant seeds, and admixtures (Chen et al., 2025; Feng & Zhang, 2024). International research originating in Japan and Germany, and recent advances in China using FLAC3D numerical simulation and field applications (Hao et al., 2023; Tang & Feng, 2025; Alavi & Mahallati, 2024; Bui et al., 2023), have demonstrated its potential. However, critical gaps persist: most studies focus on single performance indices without comprehensive evaluation systems; the long-term vegetation concrete–slope ecosystem interaction remains insufficiently understood; laboratory-based optimization methods lack field verification; and no unified technical standards exist for water conservancy applications (Peng et al., 2023; Qi & Wang, 2022).

To address these gaps, this study aimed to develop and validate an optimal design method for vegetation concrete that balances engineering performance and ecological benefits. The specific objectives were: (1) evaluating slope stability under varying slope angles (30°, 45°, 60°) and rainfall conditions (50, 100, 150 mm/24h) using FLAC3D numerical simulation; (2) assessing durability under accelerated dry–wet cycling and temperature fluctuation; (3) optimizing material ratios through L16 orthogonal experiments; and (4) validating laboratory findings through 12-month field monitoring at the Nuozhadu Hydropower Station. This integrated approach directly addresses the identified research gaps by combining comprehensive performance evaluation with field verification.

Materials and Methods

1. General

This study employed a combined research methodology integrating laboratory simulation experiments with on-site case study monitoring. The methodology included material characterization, orthogonal experiment design, FLAC3D numerical simulation, durability testing under accelerated environmental conditions, and 12-month field monitoring at the Nuozhadu Hydropower Station slope reinforcement project. All laboratory procedures were designed to simulate the environmental characteristics of the project site. The overall research workflow is summarized in Table 1.

Table 1. Summary of Research Design Workflow

Phase	Method	Key Variables	Output
1	FLAC3D Simulation	Slope angle, rainfall intensity	Safety factor, displacement
2	Durability Testing	Dry–wet cycling, temperature	Strength retention, SEM
3	Orthogonal Experiment	Cement, fly ash, red soil, agent	Optimal material ratio
4	Field Monitoring	12-month at Nuozhadu Station	Settlement, vegetation coverage
5	Integration	Lab vs. field correlation	R ² = 0.89 validation

2. Materials

The selection of constituent materials was carried out to ensure consistency with actual construction practices at the Nuozhadu Hydropower Project and to maintain experimental reliability. As summarized in Table 2, the main materials used in this study included cement, aggregate, fly ash, organic nutrient substrate, water-retaining agent, plant seeds, and mixing water, together with their corresponding specifications.

Table 2. Specifications of Materials Used in the Experimental Program

Material	Specification
Cement	Ordinary Portland Cement P·O 42.5 (GB 175-2007)
Aggregate	Graded aggregate 5–20 mm, weathered granite soil
Fly ash	Class F fly ash
Organic substrate	Humus and peat soil mixture
Water-retaining agent	Polyacrylamide-based
Plant seeds	Eulaliopsis binata and Cynodon dactylon
Water	Potable tap water

The key mechanical properties of the vegetation concrete mixture and the slope soil used in FLAC3D simulation are presented in Table 3. These parameters were determined through preliminary laboratory testing following Chinese national standards.

Table 3. Mechanical Properties of Vegetation Concrete and Slope Soil

Property	Vegetation Concrete	Slope Soil	Unit	Test Standard
Compressive strength (28d)	3.2–3.4	–	MPa	GB/T 50081
Splitting tensile strength	0.72–0.78	–	MPa	GB/T 50081
Cohesion	35.6	18.2	kPa	GB/T 50123
Internal friction angle	28.5	22.0	°	GB/T 50123
Unit weight	18.5	19.2	kN/m ³	GB/T 50123
Porosity	26–30	38–42	%	GB/T 50123
Elastic modulus	850	45	MPa	GB/T 50081

3. Experimental Design

The experimental program consisted of three main components: (1) FLAC3D numerical simulation for slope stability analysis; (2) durability simulation under accelerated

environmental conditions; and (3) orthogonal experiments for material ratio optimization. The slope angles of 30°, 45°, and 60° were selected to represent the typical range encountered in water conservancy slope engineering, from gentle to steep gradients commonly found at dam sites and reservoir embankments. Rainfall intensities of 50, 100, and 150 mm/24h correspond to light, moderate, and extreme rainfall events based on regional meteorological records for the Nuozhadu project area. These ranges cover the most critical design scenarios for slope reinforcement in subtropical monsoon climates. The experimental variables and test conditions are summarized in Table 4.

Table 4. Experimental Variables and Test Conditions

Test Component	Variables	Conditions
Slope stability	Slope angle: 30°, 45°, 60°	Rainfall: 50, 100, 150 mm/24h
Durability	Dry–wet cycling, temperature fluctuation	60-day accelerated simulation
Material optimization	Cement, fly ash, red soil, water-retaining agent	Orthogonal experiment L16

4. Experimental Program

4.1. FLAC3D Slope Stability Simulation

Slope stability was evaluated using FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) numerical simulation software. A vegetation concrete slope model was established with dimensions of 10 m × 2 m × 5 m (length × width × height), divided into hexahedral grid elements. Boundary conditions were set as follows: the left and right boundaries constrained horizontal displacement, the lower boundary constrained both horizontal and vertical displacement, and the upper boundary remained unconstrained. Mechanical parameters of vegetation concrete and slope soil including cohesion, internal friction angle, and unit weight were assigned according to preliminary test results. Three slope angles (30°, 45°, 60°) and three rainfall intensities (50, 100, 150 mm/24h) were evaluated for stress–strain distribution, displacement, and safety factor.

4.2. Durability Simulation

Durability was assessed through accelerated dry–wet cycling and temperature fluctuation simulation over 60 days. Specimens were subjected to alternating wetting and drying conditions in an artificial climate chamber. Performance indicators including compressive strength retention rate, splitting tensile strength retention rate, water absorption rate, and surface integrity were measured before and after cycling. SEM micro-analysis was

conducted to evaluate the internal cement hydration structure and aggregate–cement interface condition.

4.3. Material Ratio Optimization

Orthogonal experiments were designed with four material variables (cement dosage, fly ash replacement rate, red soil content, and water-retaining agent dosage) and three construction variables (spray-seeding pressure, curing time, and spraying thickness). Specimens were prepared and cured for 28 days under standard conditions. Performance indicators including compressive strength, shear strength, porosity, and vegetation germination rate were tested. Range analysis and variance analysis were employed to determine the optimal material ratio and construction parameter combination.

4.4. On-Site Monitoring

A 12-month field monitoring program was implemented at the Nuozhadu Hydropower Station slope reinforcement project. Five monitoring sections were arranged along the slope direction at 500 m intervals, with three monitoring points per section (slope top, slope waist, and slope foot). Monitoring indicators included surface settlement, horizontal displacement, soil moisture content, vegetation germination rate, and growth height. Monitoring frequency was daily during the first month, weekly from months 2 to 6, and monthly from months 6 to 12.

5. Data Analysis

Test results were evaluated using comparative statistical analysis and multi-index comprehensive evaluation. FLAC3D simulation outputs including safety factor, stress–strain distribution, and displacement were analyzed across all slope angle and rainfall combinations. Durability test results were expressed as retention rates relative to pre-cycling values. Orthogonal experiment data were processed using range analysis and variance analysis to identify optimal factor levels. On-site monitoring data were processed using Excel and SPSS software, with correlation analysis performed between laboratory simulation results and field data. Statistical significance was evaluated at a 95% confidence level.

Results

1. Slope Stability Simulation Results

Slope stability was significantly affected by slope angle and rainfall intensity. FLAC3D numerical simulation results demonstrated that stability decreased with increasing slope angle

and rainfall intensity. Under 50 mm/24h rainfall, all three slope angles (30°, 45°, and 60°) remained stable with safety factors of 1.82, 1.46, and 1.13 respectively. Under 100 mm/24h rainfall, 30° and 45° slopes maintained stability (safety factors 1.51 and 1.22), while 60° slopes reached the instability threshold with a safety factor of 0.97. Under the most severe condition of 150 mm/24h rainfall, only 30° slopes maintained stability (safety factor 1.24), whereas 45° and 60° slopes showed obvious displacement and failure patterns.

Table 5. Slope Stability Safety Factor under Different Working Conditions

Slope Angle	Rainfall (mm/24h)	Safety Factor	Failure State
30°	50	1.82	Stable
30°	100	1.51	Stable
30°	150	1.24	Stable
45°	50	1.46	Stable
45°	100	1.22	Stable
45°	150	0.89	Unstable
60°	50	1.13	Marginally Stable
60°	100	0.97	Unstable
60°	150	0.76	Unstable

2. Durability Simulation Results

After 60 days of dry–wet cycling and temperature fluctuation simulation, vegetation concrete demonstrated good durability with controllable performance degradation. Compressive strength retention rate was 82.3%, decreasing from 3.2 MPa to 2.63 MPa. Splitting tensile strength retention rate was 79.6%, decreasing from 0.78 MPa to 0.62 MPa. Water absorption rate increased from 15.2% to 21.7%, representing a moderate increase in porosity but with no structural cracking observed. SEM micro-analysis confirmed that the internal cement hydration structure remained intact and the aggregate–cement interface showed no obvious damage. These durability results are consistent with the findings of Hao et al. (2023), who reported compressive strength retention rates of 78–85% for vegetation concrete in high-rainfall slope environments. The slightly higher retention rate in this study may be attributed to the optimized fly ash content, which improved the pozzolanic reaction and densified the cement matrix. Compared with Bui et al. (2023), who observed significant cracking at 45 days in vegetation concrete without water-retaining agents, the absence of cracking in this study confirms the beneficial role of polyacrylamide-based agents in maintaining structural integrity under cyclic environmental loading.

3. Material Ratio Optimization Results

The orthogonal experiment identified the optimal material ratio and construction parameters suitable for the Nuozhadu Hydropower Project conditions. The optimal material ratio was determined as follows: cement dosage 320 kg/m³, fly ash replacement rate 15%, red soil content 25%, water-retaining agent dosage 0.8 kg/m³, and organic nutrient substrate 12% by mass fraction. The optimal construction parameters were spray-seeding pressure 0.6–0.8 MPa, spraying thickness 10–12 cm, and curing time 28 days. Under this optimized scheme, the 28-day compressive strength reached 3.4 MPa, vegetation germination rate was 92%, and porosity was 28%, demonstrating a balanced performance between mechanical strength and ecological function. These results align with Chen et al. (2025), who recommended cement dosages of 300–350 kg/m³ for vegetation concrete under varying moisture conditions. The 15% fly ash replacement rate in this study is within the 10–20% range suggested by Qi & Wang (2022) for sustainable vegetation concrete mixes. The achieved compressive strength of 3.4 MPa exceeds the minimum requirement of 2.5 MPa for slope reinforcement applications specified in engineering practice guidelines, while the 92% germination rate surpasses the 85% threshold reported by Feng & Zhang (2024) for native grass species in similar climatic conditions.

4. On-Site Monitoring Results

The 12-month on-site monitoring at the Nuozhadu Hydropower Station provided reliable engineering application data. Slope deformation indices remained well within safety limits: maximum surface settlement was 12.3 mm, far below the early warning threshold of 50 mm, and maximum horizontal displacement was 8.7 mm with no continuous displacement trend. Ecological performance indicators were favorable: vegetation germination rate reached 89%, consistent with laboratory simulation results; vegetation coverage rate reached 91% after 12 months; and soil moisture content stabilized at 22%–28%, suitable for sustained plant growth. No surface peeling, erosion, or slope instability occurred during the entire monitoring period. The 91% vegetation coverage achieved in this study compares favorably with Tang & Feng (2025), who reported 85% coverage at 12 months in their integrated field evaluation. The superior performance may be attributed to the optimized water-retaining agent dosage (0.8 kg/m³), which maintained soil moisture within the optimal range for sustained plant growth. The maximum surface settlement of 12.3 mm is also lower than the 18–25 mm reported by Alavi & Mahallati (2024) for conventional vegetation–soil–concrete systems, suggesting that the optimized material ratio contributes to improved long-term stability.

5. Integration and Verification

Laboratory simulation results demonstrated high consistency with on-site monitoring data, with a correlation coefficient of $R^2 = 0.89$. This strong correlation has significant practical engineering implications: it confirms that laboratory-derived design parameters can be reliably transferred to field applications, thereby reducing the need for extensive and costly field trials during the design phase of vegetation concrete slope reinforcement projects. For practicing engineers, this means that the FLAC3D simulation approach combined with the orthogonal optimization method can serve as a dependable preliminary design tool, with the expectation that field performance will closely match laboratory predictions. The verified optimal design scheme encompassed three core dimensions: material ratio (320 kg/m³ cement, 15% fly ash, 25% red soil, 0.8 kg/m³ water-retaining agent, 12% organic nutrient substrate), construction parameters (spray-seeding pressure 0.6–0.8 MPa, spraying thickness 10–12 cm, curing time 28 days), and application scope (slopes $\leq 45^\circ$ under rainfall intensity ≤ 100 mm/24h in water conservancy projects). This design framework can be directly adopted by water conservancy engineers for slope reinforcement projects under similar geological and climatic conditions, potentially reducing design iteration cycles by 30–40% compared to purely empirical approaches.

Conclusions

Based on the integrated laboratory simulation and field monitoring results, the following key conclusions were drawn:

1. Vegetation concrete slopes up to 45° maintained stability under rainfall intensities up to 100 mm/24h (safety factor ≥ 1.22). The optimized material ratio (cement 320 kg/m³, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m³, organic nutrient substrate 12%) achieved 28-day compressive strength of 3.4 MPa with 92% vegetation germination rate, demonstrating effective balance between structural performance and ecological function.
2. Durability testing confirmed 82.3% compressive strength retention after 60 days of accelerated environmental simulation with no structural cracking, indicating acceptable long-term performance. Field monitoring at the Nuozhadu Hydropower Station verified 91% vegetation coverage after 12 months with all deformation indices within safe limits.
3. The high correlation ($R^2 = 0.89$) between laboratory and field results confirmed the reliability of the integrated research methodology, enabling engineers to use laboratory-derived parameters for field design with confidence. The validated optimal design framework provides

practical guidance for vegetation concrete application in water conservancy slope reinforcement projects.

Future Work

1. Long-term durability research should be strengthened to investigate the performance of vegetation concrete under complex environments such as freeze–thaw cycling, salt erosion, and extended service periods of 5–10 years. The long-term interaction mechanism between plant root growth and vegetation concrete mechanical properties requires systematic investigation.

2. Future research should explore intelligent construction technologies combined with IoT and big data for real-time monitoring and quality control of vegetation concrete slope reinforcement. Machine learning-assisted optimization methods should be developed to improve design efficiency and accuracy for varying geological and climatic conditions.

3. The optimal design scheme should be further validated through application in diverse water conservancy project types including reservoirs, dams, and channels. The development of unified national technical specifications for vegetation concrete in water conservancy engineering was recommended to standardize material selection, construction processes, and quality control procedures.

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