



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

Mu Zhanchun<sup>1</sup>, Chaiporn Supahitanukool<sup>1</sup>, Ritthichai Ratchapan<sup>1\*</sup> and Winai Ouypornprasert<sup>2</sup>

Faculty of Engineering and Technology, Pathumthani University<sup>1</sup>

Faculty of Engineering and Technology, Pathumthani University<sup>1\*</sup>

College of Engineering, Rangsit University<sup>2</sup>

Corresponding author's e-mail: ritthichai.r@ptu.ac.th



## Abstract

Slope stability is a critical concern in water conservancy projects, yet traditional reinforcement methods such as concrete pouring and stone masonry suffer from poor ecological compatibility and high maintenance costs. Vegetation concrete — a composite of cement, soil, seeds, and additives — offers both structural strength and ecological benefits, but its optimal design remains underexplored. This study investigated the optimal design of vegetation concrete through combined laboratory experiments and on-site monitoring at the Nuozhadu Hydropower Station. Laboratory work included FLAC3D simulations (slope angles 30°–60°; rainfall 50–150 mm/24h), durability testing under dry–wet cycling and temperature fluctuation, and orthogonal experiments for material ratio optimization, followed by 12-month field monitoring. Results showed that slopes up to 45° remained stable under rainfall up to 100 mm/24h (safety factor = 1.22), with 82.3% compressive strength retention after 60 days. The optimized mix (cement 320 kg/m<sup>3</sup>, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m<sup>3</sup>, organic substrate 12%) achieved a 28-day compressive strength of 3.4 MPa and 92% germination rate. Field monitoring confirmed 91% vegetation coverage and only 12.3 mm maximum settlement, with a lab–field correlation of R<sup>2</sup> = 0.89. These findings provide practical guidance for vegetation concrete design and advance ecological slope protection technology.

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

## Introduction

Slope stability is crucial for water conservancy projects, as slope failure can cause flooding, infrastructure damage, and loss of life. Traditional reinforcement methods such as concrete pouring, anchor bolts, and stone masonry have poor ecological compatibility and high maintenance costs, disrupting soil water cycles and biological habitats (Liu & Huang, 2022; Wang & Zhang, 2022). Vegetation concrete — a composite of cement, aggregate, organic substrate, plant seeds, and admixtures — has emerged as an innovative alternative combining structural strength with ecological restoration (Chen et al., 2025; Feng & Zhang, 2024). Originating in Japan and Germany in the late 20th century and advancing rapidly in China since the 2000s, research has progressed in material design, construction technology, and FLAC3D simulation (Hao et al., 2023; Tang & Feng, 2025). However, key gaps remain: limited integrated evaluation, insufficient understanding of long-term vegetation–soil interactions, lack of field verification, and absence of unified technical standards (Peng et al., 2023; Qi & Wang, 2022). This study therefore aimed to propose an optimal design of vegetation concrete balancing engineering and ecological performance by (1) assessing slope stability under varying angles and rainfall via FLAC3D, (2) testing durability under dry–wet cycling and temperature fluctuation, (3) optimizing material ratios through orthogonal experiments, and (4) verifying results through 12-month field monitoring at the Nuozhadu Hydropower Station.

## Research Methodology

- General** This study combined laboratory simulation experiments with on-site case study monitoring. The methodology integrated material characterization, orthogonal experimental 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 replicate the environmental conditions of the project site.
- Materials** The constituent materials were selected to match actual construction practices at the Nuozhadu Hydropower Project and ensure experimental reliability. As shown in Table 1, the main materials included cement, aggregate, fly ash, organic nutrient substrate, water-retaining agent, plant seeds, and mixing water, along with their corresponding specifications.

Table 1. 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

- Experimental Design** The experimental program comprised three 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 variables and test conditions are summarized in Table 2.

Table 2. 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 software. A vegetation concrete slope model (10 m × 2 m × 5 m) was built with hexahedral grid elements. Boundary conditions constrained horizontal displacement on both sides, fully constrained the base, and left the top free. Material parameters (cohesion, internal friction angle, unit weight) were assigned from preliminary tests. Three slope angles (30°, 45°, 60°) and three rainfall intensities (50, 100, 150 mm/24h) were analyzed for stress–strain distribution, displacement, and safety factor.

**4.2 Durability Simulation** Durability was assessed through 60 days of accelerated dry–wet cycling and temperature fluctuation in an artificial climate chamber. Compressive strength retention, splitting tensile strength retention, water absorption, and surface integrity were measured before and after cycling. SEM analysis examined cement hydration structure and the aggregate–cement interface.

**4.3 Material Ratio Optimization** Orthogonal experiments combined four material variables (cement dosage, fly ash replacement rate, red soil content, water-retaining agent dosage) and three construction variables (spray-seeding pressure, curing time, spraying thickness). Specimens were cured for 28 days under standard conditions and tested for compressive strength, shear strength, porosity, and germination rate. Range and variance analyses determined the optimal combination.

**4.4 On-Site Monitoring** A 12-month monitoring program was conducted at the Nuozhadu Hydropower Station. Five monitoring sections were placed at 500 m intervals, each with three points (top, waist, foot). Indicators included surface settlement, horizontal displacement, soil moisture, germination rate, and vegetation growth height. Measurements were taken daily (month 1), weekly (months 2–6), and monthly (months 6–12).

**5. Data Analysis** Test results were evaluated through comparative statistical analysis and multi-index comprehensive evaluation. FLAC3D outputs (safety factor, stress–strain, displacement) were analyzed across all slope angle and rainfall combinations. Durability results were expressed as retention rates, and orthogonal experiment data were processed using range and variance analyses to identify optimal factor levels. On-site monitoring data were analyzed using Excel and SPSS, with lab–field correlation performed at a 95% confidence level.

## Results

**1. Slope Stability Simulation Results** Slope stability was significantly affected by slope angle and rainfall intensity, with stability decreasing as both parameters increased. Under 50 mm/24h rainfall, all slopes (30°, 45°, 60°) remained stable with safety factors of 1.82, 1.46, and 1.13, respectively. Under 100 mm/24h, the 30° and 45° slopes remained stable (1.51 and 1.22), while the 60° slope reached the instability threshold (0.97). Under the most severe rainfall of 150 mm/24h, only the 30° slope remained stable (1.24), whereas the 45° and 60° slopes exhibited obvious displacement and failure patterns.

**2. Durability Simulation Results** After 60 days of dry–wet cycling and temperature fluctuation, vegetation concrete showed good durability with controllable degradation. Compressive strength retention was 82.3% (3.2 → 2.63 MPa) and splitting tensile strength retention was 79.6% (0.78 → 0.62 MPa), while water absorption increased from 15.2% to 21.7% with no structural cracking. SEM analysis confirmed that the cement hydration structure and aggregate–cement interface remained intact.

**3. Material Ratio Optimization** Orthogonal experiments identified the optimal design for the Nuozhadu Hydropower Project: cement 320 kg/m<sup>3</sup>, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m<sup>3</sup>, and organic substrate 12%. Optimal construction parameters were spray-seeding pressure 0.6–0.8 MPa, spraying thickness 10–12 cm, and 28-day curing. This scheme achieved a 28-day compressive strength of 3.4 MPa, 92% germination rate, and 28% porosity, balancing mechanical strength and ecological function.

**4. On-Site Monitoring Results** The 12-month monitoring at Nuozhadu Hydropower Station confirmed reliable engineering performance. Maximum surface settlement was 12.3 mm (well below the 50 mm warning threshold), and maximum horizontal displacement was 8.7 mm with no continuous trend. Vegetation germination reached 89%, matching laboratory results, with 91% coverage after 12 months and soil moisture stabilized at 22–28%. No surface peeling, erosion, or instability was observed.

**5. Integration and Verification** Laboratory and field results showed strong consistency (R<sup>2</sup> = 0.89), verifying the reliability of the experimental model. The validated optimal design covered three dimensions: material ratio (cement 320 kg/m<sup>3</sup>, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m<sup>3</sup>, organic substrate 12%), construction parameters (pressure 0.6–0.8 MPa, thickness 10–12 cm, 28-day curing), and application scope (slopes <45° under rainfall ≤100 mm/24h).

## Conclusions

This study investigated the optimal design of vegetation concrete for slope reinforcement in water conservancy projects through integrated laboratory simulation and field monitoring. The main conclusions are:

- Slope stability was dominated by slope angle and rainfall intensity. Slopes up to 45° remained stable under rainfall up to 100 mm/24h (safety factor > 1.22), while only slopes <30° remained stable under extreme rainfall (150 mm/24h).
- Durability was acceptable for long-term applications: after 60 days of accelerated dry–wet cycling and temperature fluctuation, compressive strength retention reached 82.3% with no structural cracking.
- The optimized mix (cement 320 kg/m<sup>3</sup>, fly ash 15%, red soil 25%, water-retaining agent 0.8 kg/m<sup>3</sup>, organic substrate 12%) achieved a 28-day compressive strength of 3.4 MPa and a 92% germination rate.
- Field application at the Nuozhadu Hydropower Station verified effective slope reinforcement and ecological restoration, with 91% vegetation coverage after 12 months and all deformation indices within safe limits.
- The strong laboratory–field correlation (R<sup>2</sup> = 0.89) confirmed the reliability of the integrated methodology, providing a practical design scheme and technical framework for engineering applications.

## Future Work

Long-term durability research should be strengthened to investigate performance under freeze–thaw cycling, salt erosion, and extended service periods (5–10 years), along with the interaction between plant root growth and vegetation concrete mechanical properties. Intelligent construction technologies integrating IoT, big data, and machine learning should be developed for real-time monitoring, quality control, and design optimization under varying geological and climatic conditions. Broader validation across reservoirs, dams, and channels is recommended, together with the development of unified national technical specifications to standardize material selection, construction, and quality control.

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