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Carbon Sequestration Technology for Vegetated Concrete Road Embankments

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Abstract: With the rapid development of our country's economy, environmental issues have increasingly come to the forefront. In the field of slope protection engineering, traditional methods often harm the ecological environment, making the promotion of ecological civilization particularly important. Vegetated concrete, a novel slope protection material, not only safeguards slopes but also fosters ecological restoration and preservation. However, there remains a lack of systematic research on the design and application of vegetated concrete, highlighting the need for more in-depth exploration and practical implementation. This discussion analyzes ecological slopes through the lenses of the fundamental concepts and structural characteristics of vegetated concrete, vegetated concrete slope protection technology, common ecological slopes, carbon sequestration techniques in vegetated concrete slopes, and the sources of carbon emissions.

Keywords: Vegetated concrete; ecological slope protection; carbon sequestration technology; carbon fixation and oxygen release.

1. Introduction

The transportation sector in China accounts for a large proportion of carbon emissions and is growing rapidly, making it a key area for carbon reduction. In particular, road transport is the main contributor, accounting for 86% of the carbon emissions in the transportation sector. Due to the construction of roads, a large number of bare slopes have been formed along the routes, causing significant harm to the local ecological environment. To address this issue, vegetation-growing concrete technology, an innovative environmental protection measure, has emerged. Vegetation-growing concrete not only enhances the stability of slopes but also has a good carbon fixation effect. It plays an important role in promoting urban greening, improving air quality, and mitigating the greenhouse effect. Currently, in China, research on carbon reduction technologies for highway slopes is relatively limited, and there is still no unified conclusion regarding the carbon sequestration potential of ecological slope vegetation.

2. The Basic Concept and Structural Characteristics of Vegetation-Growing Concrete

2.1. Basic Concept

2.1.1. The definition of vegetation-growing concrete

Vegetation-growing concrete is an innovative building material that utilizes porous concrete as its structural framework. Plant seeds are thoroughly mixed with suitable growth substrates and filled into the internal and surface pores of the concrete. Plants can then root and germinate within these pores, integrating closely with the concrete structure to form a unified whole. This effectively increases the vegetation cover on slopes, provides structural stability, and meets the requirements for ecological slope protection[1]. Vegetation-growing concrete not only retains the mechanical properties of traditional concrete but also offers significant ecological benefits. It promotes plant growth, improves environmental quality, and achieves dual goals of carbon sequestration and ecological restoration.

2.1.2. The characteristics of vegetation-growing concrete

(1) High Strength: Its compressive strength, shear strength, and durability are all superior to those of ordinary concrete. The structural and physical properties of vegetation-growing concrete are similar to those of traditional concrete, meeting the requirements for functional use and service life.

(2) Unique Structure: Its distinctive porous structure is similar to that of "Sakima" (a type of honeycomb-like pastry). These pores not only facilitate the circulation of water and air but also provide ample space for plant roots to grow and develop, allowing them to take root and sprout.

(3) Eco-friendly: It can better adapt to the growth of microorganisms and plants, reduce carbon dioxide emissions, adjust ecological balance, beautify natural landscapes, and also alleviate the environmental burden caused by highway construction.

2.2. The Structural Composition and Properties of Vegetation-Growing Concrete

2.2.1. The Structural System of Vegetation-Growing Concrete

The structural system of vegetation-growing concrete typically consists of five components, as shown in Figure 1: the bottom soil subgrade, the vegetation-growing concrete layer, the pore nutrient substrate, the soil cover layer, and the planted vegetation. In practical applications, plant roots penetrate through the soil cover layer and the pore nutrient substrate, gradually extending into the vegetation-growing concrete layer. The internal spaces of the vegetation-growing concrete are reserved and enriched with nutrient substrates, supporting the roots to continue growing downward into the soil subgrade. This process allows the vegetation-growing concrete to integrate closely with the surrounding soil, forming a stable composite that enhances overall stability [2].

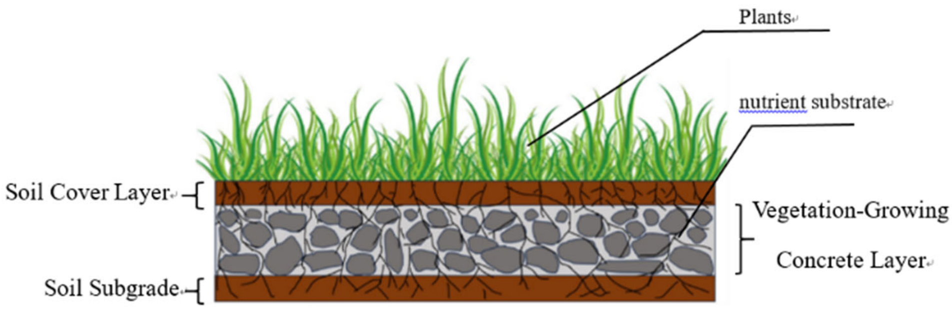

Figure 1. Vegetation-Growing Concrete Structure Diagram

2.2.2. The Properties of Vegetation-Growing Concrete

Vegetation-growing concrete is a porous concrete material composed of large-sized coarse aggregates. Its unique structure allows plants to root and develop within it. When preparing this material, the adaptability of plants must be considered. Compared with ordinary concrete, vegetation-growing concrete needs to find a balance in mechanical properties, porosity, and freeze-thaw durability, which imposes certain requirements on the material mix design. Therefore, through orthogonal experiments, it has been concluded that the porosity of vegetation-growing concrete has the greatest impact on compressive strength, followed by the amount of fly ash added, while the water-to-binder ratio and aggregate size have the least impact. The use of sulfoaluminate cement in the preparation of ecological concrete effectively controls the alkalinity of the internal structure, keeping the pH value of the pores in vegetation-growing concrete between 6.5 and 6.9, which meets the needs of plant growth. Combining the top-placing and middle-placing methods can effectively increase the survival rate of plants in vegetation-growing concrete

2.2.3. The Preparation of Vegetation-Growing Concrete

The preparation process of vegetation-growing concrete includes several steps: selection of raw materials, mix design, mixing process, forming process, and curing process.

(1) Mixing Process: The paste-coating aggregate method is used to prepare the vegetation-growing concrete mix. The specific mixing steps are shown in Figure 2.

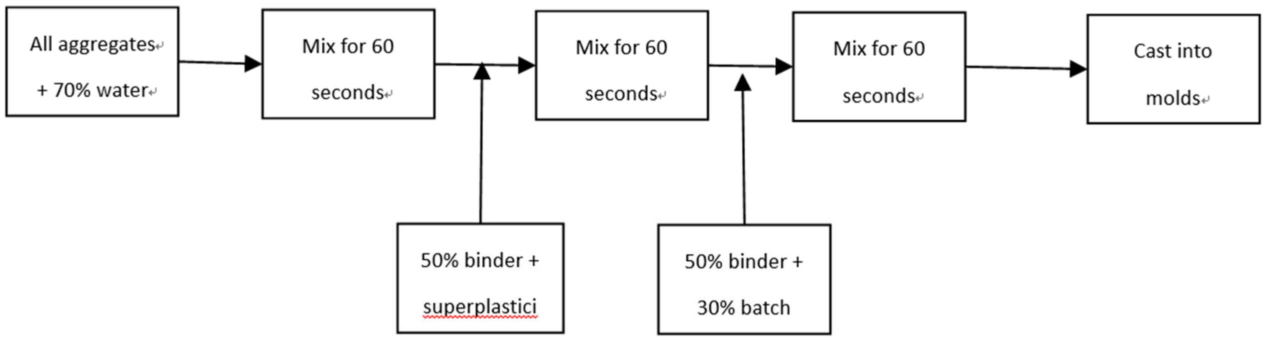

Figure 2. Preparation process of vegetation-compatible concrete mixture

(2) Forming Process: The compaction and pressing method is chosen to prepare vegetation-growing concrete. The specific steps are shown in Figure 3.

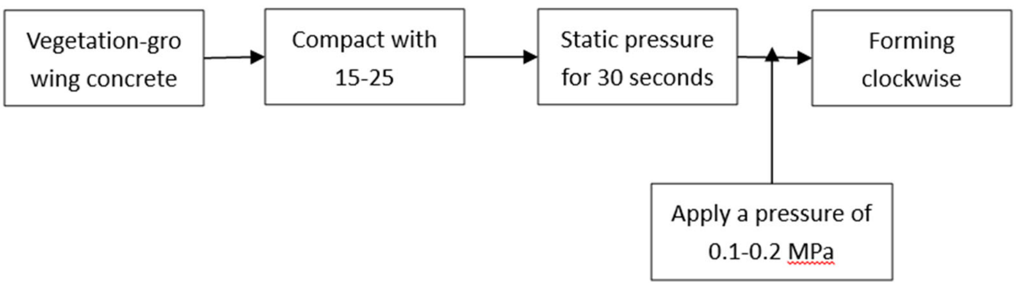

Figure 3. Formation process of vegetation-growing concrete

(3) Curing Process: After the concrete specimens are placed into molds, the molds are kept in a standard curing room to ensure hardening under optimal conditions. The specimens are demolded after 48 hours of initial setting and continue to be cured in the curing room until the specified age.

(4) Alkali Reduction Process: A combination of DPS (Deep Penetrating Sealer) permanent fluid and organic water-repellent agents is used to physically reduce the alkalinity of vegetation-growing concrete specimens after 28 days of curing. The specific method involves first air-drying the specimens, then continuously spraying the alkali-reducing solution onto the surface until it begins to drip. After allowing the specimens to air-dry naturally, this process is repeated three times.

(5) Vegetation Process: It is necessary to prepare vegetation-growing concrete, growth substrate for plants, plant seeds, alkali-reducing materials, and relevant experimental tools in advance. The specific vegetation steps are shown in Figure 4.

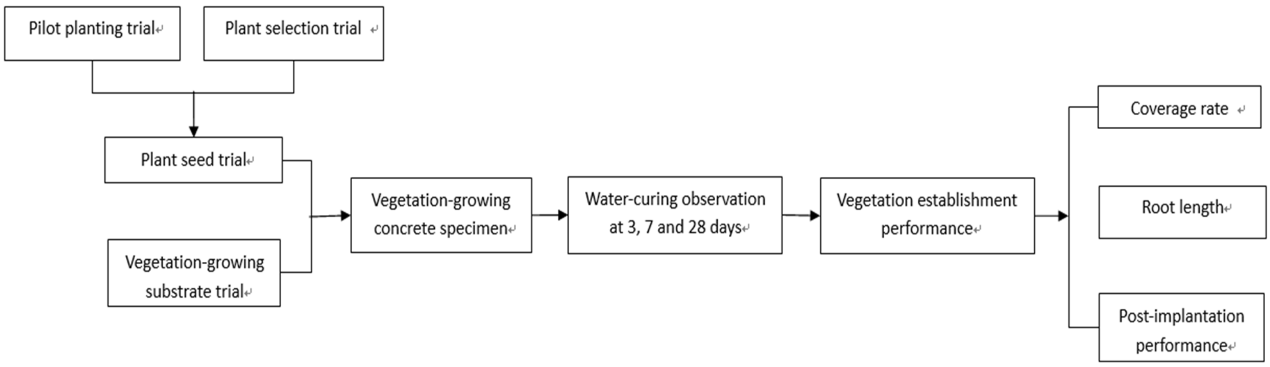

Figure 4. Vegetation process

3. Vegetation-Growing Concrete Slope Protection Technology

3.1. Ecological Slope Protection

Ecological slope protection is an interdisciplinary field that integrates civil engineering, environmental science, biology, and landscape science, emerging as a modern and innovative slope protection technology[3]. Although traditional slope protection methods offer high strength and durability, they have several drawbacks. Their surfaces are often uneven and brittle, with an unpleasant tactile quality. Moreover, the highly alkaline internal environment of traditional materials is not conducive to plant growth. These characteristics can give a rigid, rough, dull, and cold visual impression, negatively impacting ecological balance. Additionally, the production and application of traditional materials generate significant carbon emissions, exacerbating climate change[4].In contrast, ecological slope protection combines plants with non-biological materials to enhance slope stability and erosion resistance. The use of vegetation-growing concrete for slope protection effectively prevents soil erosion, landslides, and debris flows, playing a positive role in the development of ecological environment construction.

3.2. Common Types of Ecological Slope Protection

(1) Three-dimensional Geotextile Net Slope Protection: This type of slope protection is made from high molecular materials and features a three-dimensional net structure. It is used for slope protection and ecological restoration. It has ecological functions such as soil stabilization, promotion of plant growth, and enhancement of slope stability. However, it has a high initial cost, complex construction, limited plant selection, and is mainly suitable for shallow-rooted herbaceous plants. It is also highly influenced by environmental conditions.

(2) Reno Mattress Slope Protection: The Reno mattress is woven from galvanized steel wire or plastic-coated steel wire and is used for slope protection and riverbank reinforcement. The interior is filled with stones to form a robust protective layer that effectively prevents soil erosion. However, the installation and filling require specialized skills; otherwise, the protective effect will be poor, and the rough appearance can affect aesthetics. Despite its good durability, regular maintenance and management are still needed during the initial growth period of plants.

(3) Vegetation-Growing Concrete Slope Protection: Vegetation-growing concrete slope protection is a new technology that has emerged in recent years. It consists of porous concrete, vegetation substrate, water-retaining agents, and surface soil, and features high permeability, erosion resistance, and water retention. This technology requires high-quality vegetation substrate and a special concrete formula. It has certain limitations on plant species. While it performs well in the short term, its durability still needs to be verified.

4. The Application of Carbon Sequestration Technology in Vegetation-Growing Concrete Slope Protection

4.1. The Technical Principle

The carbon sequestration effect of vegetation-growing concrete slope protection technology is achieved through the following aspects:

(1) Plant Carbon Sequestration: Vegetation absorbs CO_2 through photosynthesis and stores it within plant tissues and the soil. The higher the vegetation cover, the more effective

the carbon absorption. Additionally, plant roots stabilize the soil, reducing soil erosion and thereby further decreasing carbon emissions.

(2) Soil Carbon Sequestration: Plant roots not only stabilize the soil and reduce soil erosion but also promote the accumulation of soil organic matter. Plant litter and root exudates, when decomposed in the soil, are converted into organic carbon, thereby increasing the soil's carbon storage capacity. Studies have shown that the soil organic carbon content in vegetation-growing concrete slopes is more than 20% higher than that of traditional slope protection methods.

(3) Material Carbon Sequestration: In the production process of vegetation-growing concrete, recycled aggregates and industrial by-products (such as fly ash and slag) can be used. These materials themselves have certain carbon sequestration potential.

4.2. The advantages of the carbon sequestration technology in vegetation-growing concrete

The carbon sequestration technology in vegetation-growing concrete for highway slopes has many unique advantages. Firstly, it can reduce carbon emissions, protect the environment, and enhance slope stability. Its porous structure promotes plant growth, absorbs CO_2, and achieves carbon sequestration and emission reduction. In addition, vegetation-growing concrete uses less cement than traditional concrete, reducing carbon emissions during the production process. Moreover, it has high compressive strength, and combined with plant roots, it can effectively increase the shear strength and stability of slopes. The large-pore structure also facilitates rainwater infiltration, reducing soil erosion. High vegetation coverage can improve the landscape effect and promote ecological restoration. Vegetation-growing concrete is suitable for various types of slopes, with convenient construction and wide application.

4.3. The Sources of Carbon Emissions in Vegetation-Growing Concrete Highway Slopes

The carbon emissions sources in highway slope engineering are divided into four stages: production, transportation, construction, and operation. Production stage: This includes processes such as raw material extraction, transportation, processing, and storage. The primary carbon emissions come from energy consumption, human activities, and the operation of machinery and equipment. Transportation stage: This refers to the transportation of construction materials from factories to the construction site. Carbon emissions mainly arise from the volume of transported materials, distance, energy consumption during transportation, and human activities. Construction stage: This involves on-site construction of slope protection works, with the primary sources of emissions being energy consumption and the use of machinery and equipment. Operation stage: This includes vehicle emissions, traffic congestion, routine maintenance, energy consumption of infrastructure, freight transportation, inefficient traffic management, and the impact of climatic conditions on carbon emissions[5].

5. Summary

This paper provides a comprehensive discussion on the properties and preparation methods of vegetation-growing concrete, the carbon sequestration technology applied to vegetation-growing concrete highway slopes, and the sources of carbon emissions from these slopes. The technology not only significantly enhances slope stability but also effectively promotes plant growth and increases green space, thereby achieving the dual goals of carbon sequestration and ecological restoration. Additionally, this technology offers a sustainable solution for modern civil engineering projects, contributing to environmental protection and ecological balance.

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