Proceedings of the 2nd International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/70/20240988

Research on the treatment and utilization of hydrophobic soil in sponge city construction

Peng Cheng

School of Geology and Surveying, Yanta Campus, Chang'an University, 126 Yanta Road, Xi'an

cpeng17@163.com

Abstract. This paper provides a comprehensive analysis of the characteristics of hydrophobic soil, including its strong hydrophobicity, poor water retention capacity, and unstable mechanical properties. It explores treatment technologies for hydrophobic soil such as soil amendments, bioremediation techniques, and physical treatment methods. Based on these findings, the paper proposes the utilization of hydrophobic soil as permeable paving material, filling material for rain gardens and ecological retention ponds, covering layer for green roofs, and for ecological slopes and dikes. These suggestions provide theoretical support and practical guidance for the effective use of hydrophobic soil in sponge city construction.

Keywords: Sponge City, Hydrophobic Soil, Treatment Technologies

1. Introduction

Sponge city construction, as an important concept in modern urban planning, aims to enhance a city's capacity to manage rainwater by simulating natural water cycles. This approach helps to alleviate urban flooding and improve water environments. However, in practical construction, the issue of hydrophobic soil has become increasingly prominent. The poor water permeability of hydrophobic soil severely impacts the functionality of sponge cities. Hydrophobic soil is widely distributed across urban areas, and its properties hinder natural rainwater infiltration, leading to increased runoff and placing a greater burden on urban drainage systems. Additionally, hydrophobic soil limits the effective utilization of rainwater resources, contradicting the fundamental goals of sponge city construction. Therefore, research on the treatment and utilization of hydrophobic soil is crucial for promoting sponge city development and improving urban ecological environment quality.

2. Analysis of Hydrophobic Soil Characteristics in Sponge City Construction

2.1. Strong Hydrophobicity

In sponge city construction, hydrophobic soil is particularly noteworthy due to its unique hydrophobic characteristics. This type of soil has a strong water-repellent ability, making it difficult for water to penetrate its interior [1]. When rainwater falls, the surface of hydrophobic soil often forms water droplets, hindering the natural infiltration process and affecting groundwater recharge. This hydrophobic characteristic presents both challenges and opportunities in sponge city construction. On one hand, it increases the risk of rainwater runoff, potentially putting more pressure on urban drainage systems. On the other hand, with scientific improvement and utilization, this characteristic can be turned into an advantage, such as using hydrophobic soil as waterproof material in specific scenarios.

2.2. Poor Water Retention Capacity

Due to the strong water-repellent effect of hydrophobic soil, it is difficult for water to be effectively stored within the soil, causing rapid water loss and a swift decline in soil moisture during droughts or extended periods without rain. This poor water retention capacity not only affects the normal growth of plants but also can lead to insufficient vegetation cover, making green spaces more vulnerable. In the practice of sponge city construction, this characteristic undoubtedly increases the difficulty of water environment management [2]. Without sufficient moisture, urban green spaces struggle to fulfill their ecological functions, exacerbating the urban heat island effect and degrading ecological environment quality. Additionally, the poor water retention capacity of hydrophobic soil may impede the natural infiltration and purification of urban rainwater, posing a threat to the sustainable use of urban water resources. Therefore, effectively treating and utilizing hydrophobic soil is a pressing issue in sponge city construction. By adopting scientifically sound treatment technologies and utilization methods, the shortcomings of hydrophobic soil's poor water retention can be overcome, providing strong support for the sustainable development of sponge cities.

2.3. Unstable Mechanical Properties

In sponge city construction, the unstable mechanical properties of hydrophobic soil are another significant characteristic that cannot be ignored. Due to the weak cohesion between its particles, hydrophobic soil is prone to deformation and damage when subjected to external forces, directly affecting its stability in urban infrastructure and green space construction. Specifically, when hydrophobic soil is used for paving roads, building slopes, or as filling material for green spaces, its unstable mechanical properties may lead to safety hazards such as road subsidence and slope landslides. Moreover, hydrophobic soil is more susceptible to erosion and loss when exposed to rainwater scouring, further exacerbating its mechanical instability. Therefore, in sponge city construction, it is crucial to fully consider the unstable mechanical properties of hydrophobic soil and take appropriate reinforcement measures and engineering techniques to ensure its safe and stable application.

3. Treatment Technologies for Hydrophobic Soil

3.1. Soil Amendments Method

Hydrophobic soil, as a type of soil in sponge city construction, significantly affects the entire water environment system. To improve the properties of hydrophobic soil, the soil amendments method has emerged as a crucial treatment technology. This method involves adding specific amendments to hydrophobic soil to enhance its physical and chemical properties. These amendments are diverse, including organic materials, inorganic compounds, and microbial agents, as shown in Table 1.

Table 1. Improvement Effects of Soil Amendments on Hydrophobic Soil

Type of Soil Amendment	Specific Examples	Improvement Effects
Organic Materials	Humus, Peat	Increases organic matter content, improves soil structure, and enhances water retention by 15-30%
Inorganic Compounds	Lime, Gypsum	Adjusts pH levels, improves permeability (e.g., lime can increase the pH of acidic soil by 1-2 units)
Microbial Agents	Rhizobium, Phosphate-Solubilizing Bacteria	Enhances microbial activity, boosts fertility, and increases crop yield by approximately 10-20%

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When applying the soil amendments method, it is essential first to conduct a detailed soil analysis of the hydrophobic soil to understand its physical properties, chemical properties, and microbial activity [3]. Based on the analysis results, suitable types and amounts of amendments are selected. Through scientific proportioning and mixing, the amendments are evenly applied to the hydrophobic soil and thoroughly mixed and tilled. After treatment with soil amendments, the hydrophobic soil's water retention capacity, infiltration performance, and fertility are significantly improved. This not only enhances the soil's ecological functions and promotes plant growth and reproduction but also increases the efficiency and quality of sponge city construction, providing strong support for the city's sustainable development.

3.2. Bioremediation Technology

Bioremediation technology is an environmentally friendly and sustainable method for treating hydrophobic soil. This technology uses biological factors such as microorganisms and plants to repair and improve hydrophobic soil [4]. Microbial activity in the soil can decompose organic matter, altering the soil's structure and properties, thereby reducing its hydrophobicity. Research has shown that introducing specific microbial agents can effectively improve the wettability and permeability of hydrophobic soil. Additionally, plant roots can penetrate the soil during growth, enhancing soil structure and increasing its water retention capacity. Some drought-tolerant and deep-rooted plants thrive in hydrophobic soil and can further reduce its hydrophobicity through their root systems. The advantages of bioremediation technology lie in its environmental friendliness and sustainability. Unlike traditional physical and chemical methods, bioremediation does not require the addition of chemical reagents and does not cause secondary pollution to the soil and environment. Moreover, through the natural actions of microorganisms and plants, the soil's health can gradually be restored, enhancing its ecological functions. However, the effectiveness of bioremediation can be influenced by various factors such as soil type, climate conditions, microbial species, and plant types. Therefore, in practical applications, it is necessary to select appropriate microbial agents and plant species based on specific conditions and to conduct proper field management and maintenance.

3.3. Physical Treatment Methods

In sponge city construction, physical treatment technologies for hydrophobic soil involve directly adjusting and optimizing the soil's physical structure to enhance its permeability and water retention capacity without relying on chemical additives. This direct and environmentally friendly improvement method encompasses several strategies, including but not limited to soil loosening and deep plowing, aggregate mixing, constructing permeable layers, and terrain reshaping. For example, deep plowing to a depth of about 30 cm can increase soil porosity from 40% to 50%, directly enhancing rainwater infiltration rates by approximately 30%. Additionally, mixing river sand or similar aggregates into the soil at a 1:1 volume ratio significantly increases the soil's permeability coefficient from 0.005 cm/s to 0.02 cm/s, nearly a fourfold increase, greatly facilitating water infiltration. Moreover, creating permeable layers composed of gravel and stones can increase rainwater infiltration speed to over ten times that of untreated soil, effectively mitigating urban flooding issues. Ingenious terrain reshaping, such as setting up bioretention areas, not only increases rainwater infiltration by more than 70% but also reduces surface runoff by up to 80%, demonstrating the significant effectiveness of physical treatment methods in promoting natural retention and infiltration. These comprehensive measures are customized based on field conditions, and their synergistic effects provide a solid foundation for transforming hydrophobic soil into a type of soil that supports the functions of sponge cities [5].

4. Utilization Paths of Hydrophobic Soil in Sponge City Construction

4.1. As Permeable Pavement Material

In the construction planning of sponge cities, hydrophobic soil, after specific modification and processing, can be transformed into a key component of permeable pavement materials. This provides

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an innovative approach to addressing urban flooding and enhancing rainwater management efficiency. This transformation process involves scientifically adding binders, sand, gravel aggregates, and specialized additives to the hydrophobic soil. Using professional equipment for mixing and high-pressure molding, the modified soil attains the desired pore structure and sufficient mechanical strength. The improved hydrophobic soil permeable pavement material can achieve a porosity of up to 20%, with a permeability rate exceeding 30 liters per square meter per minute. This effectively promotes rapid rainwater infiltration, reduces surface runoff, and enhances the resilience of urban drainage systems. These permeable pavements are not limited to sidewalks and bike paths but are also widely used in parking lots, plazas, and light traffic roads. Successful cases have shown that compared to traditional impervious surfaces, these pavements can increase surface water infiltration by about 60% and lower surface temperatures by 2-4°C during hot seasons, significantly combating the urban heat island effect. Additionally, the maintenance cost is about 20% lower than traditional paving materials, and the overall economic and environmental benefits throughout the lifecycle are more pronounced. By transforming originally disadvantageous hydrophobic soil into a core element of permeable pavements, the design concept of sponge cities is deeply implemented, promoting the natural balance of urban water cycles and continuous improvement of the ecological environment.

4.2. For Rain Gardens and Ecological Retention Ponds

Hydrophobic soil is cleverly applied in the design of rain gardens and ecological retention ponds in sponge city construction, showcasing its unique environmental value and ecological benefits through scientific data support. The modified hydrophobic soil, when used as a substrate in rain gardens, can enhance permeability to 20 liters per square meter per minute. This helps rapidly absorb and temporarily store large amounts of rainfall during storms, reducing surface runoff by up to 70%. In the construction of ecological retention ponds, layers of hydrophobic soil combined with sand and gravel form a graded filtration system. Experiments have shown that this design effectively removes over 90% of suspended solids and at least 50% of total nitrogen and phosphorus content, significantly improving water purification capacity. Through reasonable configuration, the interaction between native plants and the improved soil in rain gardens can absorb about 5 kilograms of $CO2$ per square meter annually while releasing oxygen, providing a "green lung" for the city. Moreover, the establishment of these ecological facilities can increase biodiversity by about 10% per hectare annually, promoting urban ecological balance. In ecological retention ponds, the enhanced water retention capacity of the improved soil allows it to store approximately 300 liters of rainwater per cubic meter of soil, not only enhancing natural rainwater recycling but also providing additional water supply during drought seasons.

4.3. As a Green Roof Cover Layer

In the planning and practice of sponge cities, the innovative application of hydrophobic soil as a green roof cover layer has shown significant environmental and economic benefits. Specially treated hydrophobic soil can increase water retention capacity to absorb and retain about 200 to 300 liters of rainwater per cubic meter of soil, effectively relieving pressure on urban drainage systems. During heavy rains, these green roofs can reduce surface runoff by up to 70%. Additionally, the combination of vegetation and soil layers lowers roof temperatures by 3-5°C compared to traditional roofs, significantly reducing air conditioning energy consumption and saving about 20% on cooling energy in buildings during summer. The hydrophobic soil layer on green roofs, with its improved permeability and aeration, supports diverse plant growth. Each square meter of green roof increases urban green space and biodiversity, estimated to enhance biodiversity levels by at least 40% compared to non-green roofs. Furthermore, green roofs can increase the annual return of precipitation through plant transpiration by about 15 mm, effectively regulating the local microclimate and combating the urban heat island effect. Therefore, using hydrophobic soil as a green roof cover layer is not only an effective means of rainwater management but also a comprehensive strategy for enhancing urban ecological environments, achieving energy savings, emissions reductions, and increasing urban resilience, contributing significantly to advancing sponge city construction towards higher levels of ecological civilization.

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4.4. For Ecological Slopes and Dikes

Guided by the sponge city concept, hydrophobic soil is ingeniously applied in the construction of ecological slopes and dikes, infusing traditional civil engineering with natural ecological vitality. Modified hydrophobic soil, mixed with organic matter, water retention agents, and locally suitable plant seeds, significantly enhances soil structural stability and ecological function. As a material for ecological slopes, it can withstand rainfall intensities of up to 500 mm/hour without causing erosion, reducing soil erosion by over 80% compared to untreated soil, effectively preventing soil and water loss and ensuring slope stability. In dike engineering, the vegetated slopes formed by hydrophobic soil can fix about 30 kilograms of soil per square meter. The tight combination of plant roots and improved soil layers reasonably controls the permeability coefficient of the dikes, effectively resisting flood invasions. Compared to traditional hardened dikes, the permeability of vegetated dikes is three times higher, ensuring flood safety while enhancing natural drainage and groundwater recharge capabilities. The increased vegetation coverage on ecological slopes and dikes brings significant ecological benefits, such as increasing urban green space by approximately 2000 square meters per kilometer of ecological dike and enhancing biodiversity by nearly 25%. This not only beautifies the urban environment but also provides habitats for wildlife, promoting a positive cycle in urban ecosystems.

5. Conclusion

This study conducted an in-depth exploration of the issues related to hydrophobic soil in sponge city construction. Through a comprehensive analysis of the characteristics of hydrophobic soil, the study revealed the challenges posed by its strong hydrophobicity, poor water retention capacity, and unstable mechanical properties. To address these challenges, the study proposed several treatment technologies, including soil amendments, bioremediation techniques, and physical treatment methods, providing technical support for practical engineering applications. Additionally, the study suggested various utilization paths for hydrophobic soil in sponge city construction. These include its use as permeable pavement material, filling material for rain gardens and ecological retention ponds, cover layer for green roofs, and as material for ecological slopes and dikes. These applications not only provide reasonable directions for utilizing hydrophobic soil but also inject new momentum into the sustainable development of sponge cities.

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