Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Assessment Of Environmental Requirements And Performance Criteria For The Permeability Of Porous Pavements

Amir Abbas Zolfaghary[1], Behrouz Behnam[2]

[1]Student at Department of Civil and Environmental Engineering, Construction Engineering Management, Amirkabir University of Technology, Tehran, Iran.
[2]Associate Professor at School of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran.

Got it! Here's the revised version with improved readability and a more natural flow:
Pavement construction is a major component of urban development and transportation infrastructure projects. Therefore, incorporating sustainable development principles at every stage—including raw material production, construction, maintenance, rehabilitation, and overall service life—is essential for preserving natural resources while reducing environmental damage caused by inefficient material use, excessive waste generation, and pollution. The adoption of modern pavement technologies has contributed, to varying degrees, to environmental protection by optimizing water consumption, reducing energy losses, and promoting waste recycling. This study systematically examines the environmental requirements and permeability performance criteria of porous pavements in Iran, aiming to clarify the reasoning behind their selection in both developed countries and the Iranian context. Additionally, it explores the environmental benefits and impacts of sponge cities, highlighting the integration of various permeable surface technologies. The concept of a sponge city is based on the fundamental idea of creating a balanced and sustainable relationship between human settlements and natural ecosystems. By enhancing urban flood resilience and reducing drought risks, sponge city initiatives enable efficient rainwater collection, infiltration, and purification within urban areas, improving water utilization and promoting long-term ecological sustainability.

Keywords: Porous pavement, Environmental criteria, Permeability performance, Urban flood management, Sustainable infrastructure

Introduction

From an environmental perspective, the realization of sustainable development is contingent upon its foundation in core ecological principles. Addressing pressing issues such as greenhouse gas emissions, climate change, depletion of the ozone layer, land degradation, the exhaustion of non-renewable resources, and urban air pollution is pivotal to advancing meaningful progress in sustainability. Pavement construction plays a critical role in urban development and must be meticulously designed to fulfill essential functions, including facilitating efficient transportation, enhancing traffic safety, and improving overall mobility. Achieving these objectives requires a holistic approach that encompasses cost-effective planning, design, construction, maintenance, resurfacing, repair, and rehabilitation, while concurrently mitigating negative environmental impacts and fostering long-term ecological sustainability (1).

The Sponge City Initiative introduces a groundbreaking and highly effective strategy for mitigating the urban heat island effect and alleviating urban flooding. A sponge city is distinguished by its exceptional resilience to environmental fluctuations and natural disasters, operating analogously to a sponge that efficiently absorbs and regulates water dynamics. This urban paradigm is designed to capture, absorb, store, and purify rainwater, subsequently releasing and utilizing the retained water as required. The implementation of sponge city principles yields substantial environmental and infrastructural advantages, such as the preservation of urban ecosystems and the restoration of disrupted hydrological cycles, thereby optimizing urban water management. Within this framework, the integration of eco-friendly and permeable concrete is pivotal in harmonizing green construction practices with the sponge city model. By assessing its performance and efficacy, this sustainable material has the potential to make a significant contribution to advancing climate-resilient urban development and fostering environmentally responsible construction methodologies. (2)

In contrast, the underlying ground of traditional roadways is inherently impermeable to water. Given the frequent incidents of roadway flooding and the heavy dependence on drainage pipe systems, the primary approach for managing urban flooding has been the regulation of surface runoff through these drainage infrastructures. However, with the rapid and ongoing urban expansion, municipal infrastructure has failed to keep pace with the escalating demands of construction and development. As a result, urban drainage systems are increasingly unable to effectively address the drainage requirements of modern cities. During heavy rainfall events, the accumulation and uncontrolled flow of stormwater presents substantial risks, placing considerable strain on urban flood management strategies. Permeable pavements, with their exceptional capacity for water infiltration, present a viable solution by significantly reducing the urban surface runoff coefficient, shortening peak flow durations, easing the burden on drainage systems, and ultimately mitigating the overall pressure on urban flood control measures. (3)

The concept of a sponge city primarily underscores its capacity to effectively mitigate the impacts of natural disasters and environmental fluctuations. This urban model operates similarly to a sponge, proficiently absorbing rainwater during precipitation, storing it, and purifying it for later use. When required, the stored water can be utilized with optimal efficiency. As previously discussed, the integration of permeable concrete pavements has become increasingly critical in alleviating localized urban flooding and enhancing the efficacy of urban drainage systems. Furthermore, the design of underground reservoirs, rainwater-irrigated gardens, and submerged green spaces significantly improves the city's capacity for rainwater retention. These integrated solutions provide a more resilient and sustainable response to the challenges posed by urban water scarcity. In light of these considerations, the objective of this research is to critically assess the environmental requirements and performance criteria related to the permeability of porous pavements in Iran.

Performance Requirements for the Permeability of Porous Pavements in Sponge Cities

1. **Permeability Coefficient**

The permeability coefficient (κ), commonly referred to as hydraulic conductivity, is defined for any homogeneous medium as the ratio of flow rate to the hydraulic gradient. This coefficient represents the ease with which a fluid can move through porous materials. It is mathematically expressed by the following equation (1):

$$\kappa = \frac{k\rho g}{\eta}$$

In this equation, k denotes the permeability of the porous material, which is fundamentally determined by the inherent properties of the material and the arrangement of its solid structure. The variables are defined as follows: κ represents the permeability coefficient, η is the dynamic viscosity coefficient, ρ is the fluid density, and g is the acceleration due to gravity.

Figure 1: Hydraulic Conductivity and Water Retention Capacity of Permeable Concrete

Certainly! Here's a more refined version suitable for an academic context:
The permeability coefficient, denoted as κ, is expressed as a tensor for homogeneous materials and serves to quantify a material's capacity to transmit water. A higher permeability coefficient is associated with an enhanced ability to facilitate water flow. In the case of highly permeable coarse-grained gravel layers, κ exceeds 10 meters per day, while in low-permeability subsoil layers, it ranges between 1 and 0.01 meters per day. For nearly impermeable clay, the permeability coefficient is less than 0.01 meters per day (4).
Water permeability and compressive strength are two fundamental, yet inherently contrasting, properties of permeable concrete. To assess water permeability, the concept of effective porosity is frequently employed. In an extensive study conducted by Zhang Mulin and colleagues at Chang'an University, the relationship between compressive strength and effective porosity was systematically investigated. The findings revealed a robust correlation between these parameters, with a correlation coefficient of R = 0.8631, signifying a notable interdependence.

$$f_{c,7} = -0.3806n_e + 17.058 \qquad (2)$$

In this equation, $f_{c,7}$ denotes the compressive strength, whereas n_e represents the effective porosity of the material, which directly influences its permeability and structural integrity.
A well-defined linear correlation can be derived between the compressive strength ($f_{c,7}$) and the effective porosity (n_e) of porous concrete. This relationship is of paramount importance in optimizing the design parameters and theoretical calculations for the mix proportioning of permeable concrete, facilitating an optimal balance between mechanical strength and hydraulic performance.

2. Factors Influencing the Permeability Coefficient

The water permeability coefficient of surface treatments for roads within a sponge city is primarily influenced by factors such as porosity, adhesive strength, and the size of aggregate particles. Among these, porosity is widely regarded as the most significant factor affecting the durability and performance of permeable surface treatments. In engineering practice, it is crucial for these treatments to not only exhibit sufficient structural strength but also facilitate the controlled infiltration of water. To achieve the requisite permeability performance for permeable roads, the effective porosity typically needs to fall within the range of 15% to 25% (5).

3. Research and Applications of Permeable Concrete

Since the early 21st century, China has implemented a range of initiatives to promote the utilization of permeable concrete. In 2004, permeable concrete roads were introduced in five exhibition districts of Beijing, serving as a replacement for traditional urban roadways, coupled with the installation of rainwater harvesting systems designed to meet the irrigation needs of green spaces. This approach has proven particularly effective in managing heavy rainfall and has been extensively applied for various purposes, such as providing water for domestic cleaning, powering fountains, supporting water features in central public squares, and replenishing groundwater reserves. Moreover, the development of rainwater collection reservoirs has significantly reduced the strain on urban pedestrian walkways and parking areas by alleviating flooding pressures.
In 2008, permeable concrete, along with the concrete used in the construction of the Olympic facilities, covered an area of approximately 103,117 m^2. In this system, rainwater is absorbed through the concrete fountains and directed into a perimeter drainage network alongside the pathways. The collected water is then routed through the system to a discharge point, where it is repurposed for use within the stadium (6).
In Shanghai, permeable concrete has been systematically incorporated into both newly designed drainage systems and the renovation of existing infrastructure. By 2010, more than 60% of the pavements at the Expo site, including key areas such as the central Expo Beach, Expo Park, the flooring within the park, and Africa Square, were constructed using permeable concrete. Extensive evaluations conducted after multiple rainfall events indicated that permeable concrete facilitates the swift infiltration of rainwater into the ground. As a result, the surface eliminates light reflection at night, enhancing safety and comfort for road users. Furthermore, the urban heat island effect is significantly alleviated, contributing to a more sustainable and pleasant urban environment (7).
In 2009, Youdao Square, located within the Xiandaming Palace National Heritage Park, was paved with permeable concrete across a substantial area of 150×10^3 m^2, yielding highly effective performance. However, in China, the design specifications, standards, and technical

regulations governing the construction of permeable concrete have yet to be established. The absence of such standards may negatively impact both the construction process and the oversight of permeable concrete projects, potentially undermining their long-term success.

4.Recommendations for Enhancing the Water Permeability of Permeable Pavements

In-depth and systematic research is required to examine both the microscopic and macroscopic structures of the materials constituting permeable concrete. This research should aim to expand knowledge of its physical and mechanical properties, with a particular focus on enhancing compressive strength, bending strength, and long-term durability. Additionally, it is imperative to investigate the factors influencing the permeability performance of permeable concrete, identify viable solutions, and assess their practical feasibility. Experimental studies conducted in real-world contexts are essential to evaluate the environmental benefits of permeable concrete, including its potential to improve air circulation, facilitate water absorption, reduce noise, and enhance water quality. Such findings will further support its incorporation into broader environmental protection strategies. Moreover, the development of comprehensive national standards for the design, construction, maintenance, and management of permeable concrete mixtures is critical to fostering its widespread adoption and integration across the country (8).

5.Economic and Environmental Resource Savings with Green and Eco-friendly Porous Concrete

This study involved the analysis of several porous concrete samples to evaluate their evaporative properties. One of the significant benefits of green, eco-friendly porous (spongy) concrete is its reduced cement requirement, which consequently leads to a decrease in CO2 emissions. To conduct a comprehensive comparative and quantitative assessment of the economic and environmental performance of porous concrete, a pavement was constructed along a park walkway with dimensions of 50 meters in length, 1 meter in width, and 0.1 meters in thickness. The data gathered revealed that the production of one ton of cement results in approximately 653.38 kilograms of carbon dioxide emissions, with the cost of producing one ton of conventional cement amounting to 635.5 yuan. A comparative analysis based on these findings was performed, and the results are presented in Table 1 (9).

Table 1: Mix Ratios of Permeable Concrete

Type	Cement Content in Concrete (tons)	CO2 Emissions (kg)
Ordinary Concrete	1.99	1300.23
Green and Eco-friendly Porous (Spongy) Concrete	1.52	993.14

The comparative analysis of the results indicates that the adoption of green, eco-friendly porous (spongy) concrete facilitates a reduction of 0.47 tons in cement consumption, yielding a cost savings of 298,685 yuan. Furthermore, this approach results in a decrease of 307.09 kilograms in CO2 emissions, demonstrating its environmental and economic benefits.

6.Water Storage Efficiency in Sponge Cities

A number of studies have highlighted the lack of uniformity in the standards established for the construction of sponge cities. Despite the presence of various criteria within this field, these standards have not yet been widely adopted or sufficiently developed. Consequently, this paper categorizes the criteria related to rainwater harvesting in sponge cities into three main groups. Assuming the use of permeable concrete for rainwater collection in all instances, these categories include: "criteria for rainwater collection," "criteria for water storage," which pertains to the storage and treatment of rainwater, and "criteria for water consumption," which focuses on the efficient use of harvested rainwater.

Rainwater collection and storage reservoirs typically comprise eight fundamental components. These include the tank structure, sedimentation well, water well, top and bottom ventilation covers, inlet and outlet pipes, aeration system, and overflow pipe. Additionally, depending on the selection of plant species, the treatment of the groundwater table should be specifically tailored to ensure effective and efficient management.

In the design of a garden incorporating a rainwater irrigation system, the surrounding area is envisioned as a grassland, where rainwater runoff is initially gathered and subsequently directed into a buffer zone. This buffer zone, typically covered with fine sand, serves to filter out impurities from the rainwater while effectively slowing its flow. Simultaneously, it acts as a protective boundary, where moisture-resistant plants are strategically placed. The design ensures that the flow of water is moderated as it traverses the buffer zone, thereby minimizing the direct impact of the rainwater's force on the plants (4).

In the urban landscaping of various cities, the practice of inundating green spaces with harvested rainwater has proven to be highly effective. This technique is specifically aimed at enhancing the storage capacity for rainwater by flooding designated green areas, thus facilitating both the storage and treatment processes. Typically, this approach is realized through the incorporation of wet ponds, wetlands, and biological retention systems, which collectively play a crucial role in the efficient management and purification of the water (10).

Environmental Standards

In large urban environments, where expansive impervious surfaces and limited vegetation prevail, solar radiation is quickly absorbed and re-emitted as thermal energy, exacerbating the urban heat island effect. This leads to substantial temperature differences between areas dominated by materials such as asphalt and concrete, and those enriched with vegetation. The urban heat island phenomenon, influenced by local wind patterns, encourages cloud formation, enhances precipitation, and increases lightning frequency, thereby altering local weather patterns and broader climate conditions. Moreover, the elevated temperatures result in heightened energy consumption for cooling, which further degrades urban air quality, contributing to discomfort and negatively affecting the health and well-being of urban populations (11).

Effective water resource management, particularly in relation to surface runoff and stormwater, is paramount in addressing urban water challenges. It is proposed that an optimal strategy entails the adoption of advanced management practices that direct water through specific channels, ensuring its proper storage, treatment, and subsequent utilization for green spaces and urban infrastructure. This approach not only fosters water conservation but also mitigates the impact of water scarcity, especially in terms of potable water supply. In addition, such strategies contribute to the development of more sustainable and economically viable green spaces. Furthermore, the standard includes comprehensive measures for the storage and reuse of treated water, thus supporting long-term environmental and urban sustainability. A key criterion addressed in this framework pertains to the impermeability of road surfaces. The choice of materials and design strategies directly influences both the extent of vehicle-induced pollution and the subsequent cleaning demands. Equally important is the efficient utilization of energy resources and waste management, which form fundamental aspects of the standard. These provisions also encompass the operation of street lighting systems during nighttime hours, with a particular focus on evaluating their energy consumption. Moreover, the standard is especially relevant for areas where road surfaces are exposed to dry conditions, ensuring the adoption of materials that enhance energy efficiency and facilitate optimal heat dissipation. In such contexts, the degree of light reflection and its effect on energy conservation are of paramount importance. Additionally, this section considers the energy required for the production of primary materials, vehicle upkeep, and the recycling of waste materials for reuse, further contributing to the standard's comprehensive sustainability goals (12).

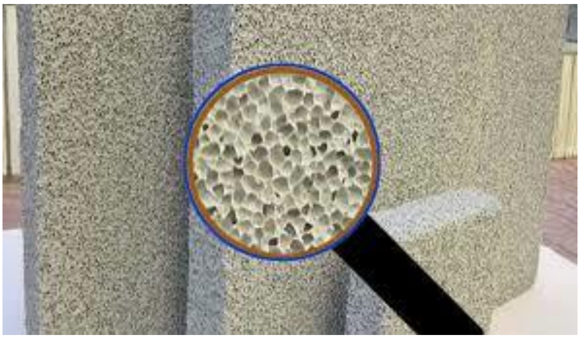

Figure 2: Microscopic Section of Sponge Concrete

The safety coefficient of roadways has been the focus of extensive research, particularly about reducing slipperiness and improving light reflection on icy surfaces, which are crucial for driving safety. Key factors within this standard include enhancing skid resistance or friction, especially under normal traffic conditions and during inclement weather, such as icy or wet conditions. Additionally, maintaining a smooth and uniform road surface is essential to ensuring consistent safety performance and optimal driving conditions.

The overall performance of road maintenance is typically assessed through two primary dimensions: functional performance and structural performance. Functional performance pertains to the ability of the road infrastructure to provide essential services to its users, emphasizing aspects such as driving comfort, road surface quality, and overall user experience. This includes considerations such as surface smoothness, driving ease, and the reduction of noise-related discomfort. In contrast, structural performance focuses on the physical soundness of the roadway, addressing concerns such as cracking, surface degradation, and other forms of deterioration that directly impact the road's load-bearing capacity. The Road Maintenance Regulations (2011) offer a comprehensive functional performance analysis, emphasizing that effective maintenance practices lead to enhanced surface quality. These improvements contribute to a more favorable user experience by reducing noise pollution, mitigating fatigue from road vibrations, ensuring smoother travel conditions, and decreasing vehicle wear, such as tire and suspension damage. Moreover, diligent maintenance is crucial in reducing traffic disruptions, particularly during flood events, thereby enhancing road safety and operational reliability (12).

The annual index of flood-induced damage to infrastructure emphasizes the vital role of pavement systems in mitigating these impacts. Pavements designed with improved porosity effectively reduce surface runoff, thereby alleviating flood-related damage and significantly enhancing the resilience of road infrastructure.

Furthermore, the annual service cost index encompasses a wide spectrum of expenses, including the upkeep of road surfaces, management of drainage systems, snow and ice removal operations, as well as the periodic reapplication of lane markings. It also incorporates costs associated with labor, specialized maintenance equipment, and the installation of noise-reducing barriers. Collectively, these components contribute to the overall financial burden of maintaining road infrastructure, ensuring both its safety and operational efficiency (13).

The service life of pavement refers to the period during which its functional performance transitions from its optimal condition to a level deemed minimally acceptable. Pavement serviceability is defined as its capacity to provide a safe, comfortable, and efficient driving experience for users. This performance is typically assessed using indicators such as surface roughness and structural degradation, including cracking, patching, and rutting. The evaluation of pavement serviceability involves periodic measurements of its performance index at defined intervals over its design and operational life. Initially, pavements exhibit peak service quality; however, with prolonged use and exposure to environmental conditions, their performance progressively deteriorates. The primary contributors to this decline are the intensity of traffic load and environmental factors. According to the 2011 Pavement Design Code, essential durability parameters encompass resistance to freeze-thaw cycles, degradation caused by chemicals and petroleum, and the pavement's compressive, tensile, and flexural strength. These factors are integral to maintaining the long-term structural stability and functional efficacy of pavement systems.

The annual maintenance and repair expenditures for porous pavements encompass costs associated with crack sealing, patching, rut remediation, surface leveling, and pothole rehabilitation. Additionally, these costs include the expenses for materials, equipment, and labor, which collectively exert a substantial impact on the overall maintenance budget.

Given the relatively novel construction techniques employed for porous asphalt, roller-compacted concrete, and pervious concrete, a higher safety margin has been factored into the cost assessment for their production and implementation.

Technological advancements in pavement construction and rehabilitation are considered across two critical areas: execution and maintenance. Due to the advanced technologies employed in the construction of porous asphalt and pervious concrete, an elevated safety margin has been integrated into their cost evaluation criteria, ensuring their sustained performance and long-term durability.

Conclusion

In modern urban governance, the concept of the "Sponge City" has gained significant prominence as a critical focus of discussion. This paradigm envisions urban spaces with a high degree of flexibility, akin to the porous nature of a sponge, enabling them to effectively absorb and adapt to environmental variations while mitigating the negative consequences of natural disasters. The development of Sponge Cities must be guided by a core principle of ecological precedence, ensuring that environmental considerations are prioritized in urban planning. In light of the crucial role of rainwater harvesting in meeting regional water demands, particularly in China, the widespread promotion of Sponge Cities is of paramount importance. To guarantee the sustained success of this initiative, it is essential to establish a comprehensive regulatory framework that consistently monitors both current conditions and future development trends. Additionally, an integrated and dynamic oversight mechanism, coupled with periodic evaluations of the infrastructure, should be implemented to assess the efficiency and sustainability of Sponge City systems, fostering urban resilience and ecological adaptability over the long term.

The green and eco-friendly porous (sponge) concrete demonstrates a water retention capacity more than twice that of traditional concrete, while also offering enhanced cooling performance and superior water permeability. When utilized as a paving material, it exhibits a water retention rate of 6.96 kg/m^2 and a water infiltration rate of 1.78 $kg/s/m^2$. The porous structure, characterized by interconnected voids, facilitates increased water absorption, thereby significantly reducing evaporation rates compared to conventional concrete. This unique attribute not only improves the pavement's stormwater management capabilities but also contributes to the reduction of surface temperatures, enhancing urban thermal regulation and fostering more sustainable urban environments.

In summary, porous (sponge) concrete, recognized for its environmental sustainability and eco-friendly characteristics, offers considerable potential for a wide range of engineering applications, particularly in the context of sponge city infrastructure development. Its implementation is instrumental in the creation of resource-efficient, ecologically responsible urban environments. Moreover, its use can provide notable social and economic benefits, including energy conservation, environmental protection, and the promotion of sustainable construction practices. When incorporated into the design of concrete pavements and ecological filtration systems within sponge city frameworks, porous concrete demonstrates enhanced functional performance. Consequently, it is poised to emerge as a pivotal material in the advancement of "sponge cities," contributing to the development of more resilient and sustainable urban landscapes.

References

1. Sun, X., Study on Engineering Performance of Green Porous Sponge Ecological Concrete. Advances in Materials Science and Engineering 2021(8269053).
2. Zhengwei Zhang, A.S., Xiang Liu, Bo Luan, Jie Gao, Wei Jiang, Feng Ma, State-of-the-art of porous asphalt pavement: Experience and considerations of mixture design. Construction and Building Materials 2020. **262**(119998).
3. Andersson, R. & Carlsson, V., 1990. Interaction between mix design, construction and properties for RCCP, 6th international symposium on concrete roads, Madrid, Cembureau, Brussels.
4. Bourgeois, M. M. & HERSEL, O.: "Roller compacted concrete for pavements in military areas within the Federal Republic of Germany". 6th international symposium on concrete roads, Madrid, Cembureau,Brussels.
5. Xu. Jinhua, Chen Sili, Wang Ying, Li Gang, Research on mixture design and mechanical performance of porous asphalt concrete in cold regions, Adv. Mater. Res. 299–300 (2011) 770–773.
6. Jian Shih Chen, Shih Fan Chen, Min Chih Liao. Laboratory and Field Evaluation of Porous Asphalt Concrete. Asian Transport Studies, 3(3), 2015.
7. Weiguo Shen, Lai Shan, Tao Zhang, Hongkun Ma, Zhi Cai, Hu.a. Shi, Investigation on polymer–rubber aggregate modified porous concrete, Constr. Build. Mater. 38 (2013) 667–674.

8. Nurul Athma Mohd Shukry, Norhidayah Abdul Hassan, Mohd Ezree Abdullah,et al. Influence of diatomite filler on rheological properties of porous asphalt mastic. International Journal of Pavement Engineering. DOI:10.1080/ 10298436.2018.1483504.
9. D. Little, J.C. Petersen, Unique effects of hydrated lime filler on the performance-related properties of asphalt cements: physical and chemical interactions revisited, J. Mater. Civ. Eng. (ASCE) 17 (2) (2005) 207–218.
10. Moisture sensitivity of asphalt pavement (a national seminar).Transportation research board of the national academies, San Diego,California, February, 2003.
11. Wang Xiaowei, Gu Xingyu, Dong Qiao, Wu Jiangtao. Effects of flat and elongated aggregates on the performance of porous asphalt mixture. Journal of Southeast University (English Edition) 34(1), 2018.
12. Zhang Wangchen, Experimental Study on Pavement Performance of Fiber Asphalt Mixture Master degree thesis, Hefei University of Technology, Hefei, China, 2019.
13. Jiliang Feng, Study of Performance and Mechanism of Fiber Reinforced Asphalt Mixtures Doctor of Philosophy, Southeast University, Nanjing, China, 2006.
14. Song Li, The Study on Application of Fiber Asphalt Concrete Master degree thesis, Hebei University of Technology, Hebei. China, 2011.