Environmental Science and Pollution Research (2024) 31:40818–40837
https://doi.org/10.1007/s11356-024-33760-6

REVIEW ARTICLE

Application of pervious concrete pavement in the "breathe in-breathe out" design for sponge cities in China

Yu Huang[1] · Hao Sun[1] · Yuhang Liu[2] · Kai Zhao[2] · Tong Liu[3] · Dedi Liu[2]

Received: 4 February 2024 / Accepted: 17 May 2024 / Published online: 2 June 2024

Abstract

Sponge city construction is an ideal approach to mitigate the degradation of urban water environments. Among road materials, permeable concrete pavement stands out due to its unique structure that allows rainwater runoff to flow through its pores. This paper analyzes the current application status and the prospect of different permeable pavement designs in China's sponge cities, aiming to offer valuable insights for urban planning and construction. Statistical analysis summarizes the spatial-temporal distribution patterns of urban flooding disasters in China and their causes. By comparing the characteristics and advantages of pervious concrete pavement with traditional concrete pavement, the potential of permeable concrete pavement in sponge city construction is summarized through case studies. The findings highlight that by adjusting the pore size, permeable concrete pavement can collect rainwater while filtering impurities, thereby purifying surface runoff. The range of the pervious coefficient should ideally fall within the range of 4~8 mm/s. In addition, the pavement's large contact area with the air and internal water evaporation contributes to its self-regulating capability, reducing the occurrence of extreme temperatures. Related experiments have shown that from 8 am to 12 pm, pervious concrete pavement can reduce the temperature by approximately 1 °C compared to conventional concrete. From 12 pm to 8 pm, this temperature difference increases to approximately 3 °C. To meet the needs of environmental protection and resource utilization, permeable concrete pavement can serve as an ideal tool to achieve green and low-carbon development.

Keywords Sponge city · Permeable concrete · Urban flooding prevention · Green infrastructure material

Introduction

China's rapid economic and social development has intensified environmental pollution. Factors such as industrial wastewater, urban vehicle exhaust emissions, pesticide usage, and domestic sewage discharge have significantly contributed to this negative impact. In recent years, many cities in China have been confronted with ecological disasters such as frequent water flooding, serious water environmental pollution, and water resource shortage, particularly during the rainy season (Nguyen et al. 2019; Sarkar et al. 2021; Stanczuk-Galwiaczek et al. 2018; Uribe et al. 2022). According to the latest data from the Ministry of Water Resources in 2020, the direct economic loss caused by flood disasters alone across the country exceeded 80 billion yuan (Chan et al. 2018). Urban water flooding not only causes serious economic losses within the affected region but also poses a threat to the safety of citizen's lives and urban infrastructure (Tang et al. 2024). Urban roads, which account for approximately 15–20% of the urban area, serve as crucial infrastructural links connecting cities, regions, and plots. However, the widespread use of impervious pavement, such as asphalt, has replaced the naturally permeable underlying surface, resulting in the doubling of urban surface rainwater runoff and peak flows. Consequently, this has exacerbated non-point source pollution and highlighted the limitation of impervious concrete. In recent years, water flooding

---

Responsible Editor: Philippe Garrigues

✉ Hao Sun
sunhao7572@nwu.edu.cn

[1] Shaanxi Provincial Key Laboratory of Surface System and Environmental Carrying Capacity, College of Urban and Environmental Sciences, Northwest University, Xi'an 710127, China

[2] School of Highway, Chang'an University, Xi'an 710064, China

[3] School of Science, Xi'an University of Architecture and Technology, Xi'an 710055, China

incidents have become increasingly frequent in China. For example, the rainfall in July 2022 in Kunming led to overflowing water from main road intersections onto sidewalks, leaving numerous vehicles trapped. Similarly, the "7.20" rainstorm in Zhengzhou in 2022 and the "7.24" rainstorm Urban flooding in Xi'an in 2016 resulted in the recurring occurrence of "urban seas," as shown in Fig. 1. What is the way forward?

Impermeable urban roads and pavement are major contributors to the high pressure of flood discharge in modern cities. The extensive use of impermeable concrete on roads has significantly reduced the water and air permeability, as well as the attainability of the pavement. Consequently, excessive rainfall severely hampers drainage capacity, leading to water flooding and related issues. At the same time, due to the small pores of traditional roads, it is difficult to direct heat exchange with the atmosphere, resulting in the urban heat island effect and noise pollution. Urgent solutions are needed to address these ecological challenges in urban areas. Urban roads with sponge functions contribute greatly to urban runoff control. Therefore, incorporating the concept of a sponge city into the optimization of traditional urban roads and exploring new pavement materials or improving raw materials can effectively alleviate the drainage pressure of urban roads and reduce non-point source pollution. As a new environmentally friendly pavement material, permeable concrete has gradually gained significant attention. It consists of modified cement, water, a pervious agent, and a concrete-specific reinforcing binder (known as pervious cementation mixture) mixed with high-quality aggregates of the same particle size or with a large discontinuous pervious grade, resulting in a certain degree of porosity. Compared to traditional concrete, permeable concrete possesses numerous interconnected pores, excellent air, and water permeability and can significantly reduce the runoff coefficient of rainwater. Its application on urban roads not only expands the water and air permeable areas of the cities, enhancing the comfort and safety of pedestrians, but also plays a crucial role in regulating urban air temperature, humidity, groundwater levels, and ecological balance. While research and development on permeable concrete began in Europe, the USA, Japan, and other regions in the 1980s, China's exploration of this material only commenced in the 1990s, warranting further investigation into its unique characteristics. Based on this consideration, this paper examines and consolidates the relevant characteristics of permeable concrete, with a specific focus on water permeability, heat absorption, and purification. Furthermore, it explores the application status and new design of permeable concrete in the construction of the "breathe in-breathe out" concept within sponge cities, aiming to contribute to mitigating urban flooding concerns and advancing sustainable urban development.

Fig. 1 Water flooding in typical cities in China

Background and temporal-spatial distribution of sponge city construction

Characteristics of urban water flooding in China

In terms of a time dimension, China experiences a significant amount of precipitation, with an average annual precipitation of 631.5 mm (Ministry of Water Resources of China, Annual Report on China's Water Resources 2023). Affected by the southeast monsoon and southwest monsoon, China's precipitation shows substantial inter-annual variations and uneven seasonal distribution throughout the year, mainly concentrated from June to September (accounting for 60 to 80% of the total precipitation), and even exceeding 90% in the northern regions (Zhang et al. 2017; Wu and Fu 2013). Consequently, every summer is characterized by frequent instances of flooding. However, due to the high peak flow during the flood season, most of them are not fully utilized and infiltrated, resulting in alternating river interruption and floods, with an increasing risk of disaster. According to the related data, the ratio of maximum peak discharge to the average annual maximum peak discharge is 5–10 times in the north and 2–5 times in the south. This disparity in magnitude occurs within and between years, increasing the risk of flood disasters. Turning to the spatial dimension, China, with obvious spatial distribution disparity, generally presents a natural trend of "water flooding in the South and drought in the North."

According to Fig. 2, the intensity of rainstorms has been consistently increasing in developed coastal provinces and cities, as well as in central and western regions such as Shaanxi, Gansu, and Qinghai. This suggests that in the future, urban rainstorms may become more severe. Global warming, dominated by the urban heat island effect, has a significant impact on urban micro-rainfall, leading to a reduction in annual precipitation in urban areas. The combined effects of extreme climate events and urbanization have resulted in a heightened risk of frequent rainstorms and floods, as well as an increase in peak flood volumes. Changes in the urban land surface directly affect the infiltration and runoff of rainwater, posing security risks (Qiu et al. 2024a, b). Statistics reveal that between 2007 and 2017, more than 360 cities across the country experienced flooding, especially in mega-cities and provincial capitals. For instance, in 2021, 380 people died and disappeared due to the "7.20" rainstorm in Zhengzhou, with an economic loss of 40.9 billion yuan; similarly, the "5.22" rainstorm in Guangzhou in 2020 led to flooding in 443 areas of the city, resulting in the shutdown of Metro Line 13 and the suspension of classes in many places (Cui et al. 2023). Additionally, the "4.11" rainfall event in Shenzhen in 2019 triggered a flood, causing 11 workers to drown while cleaning

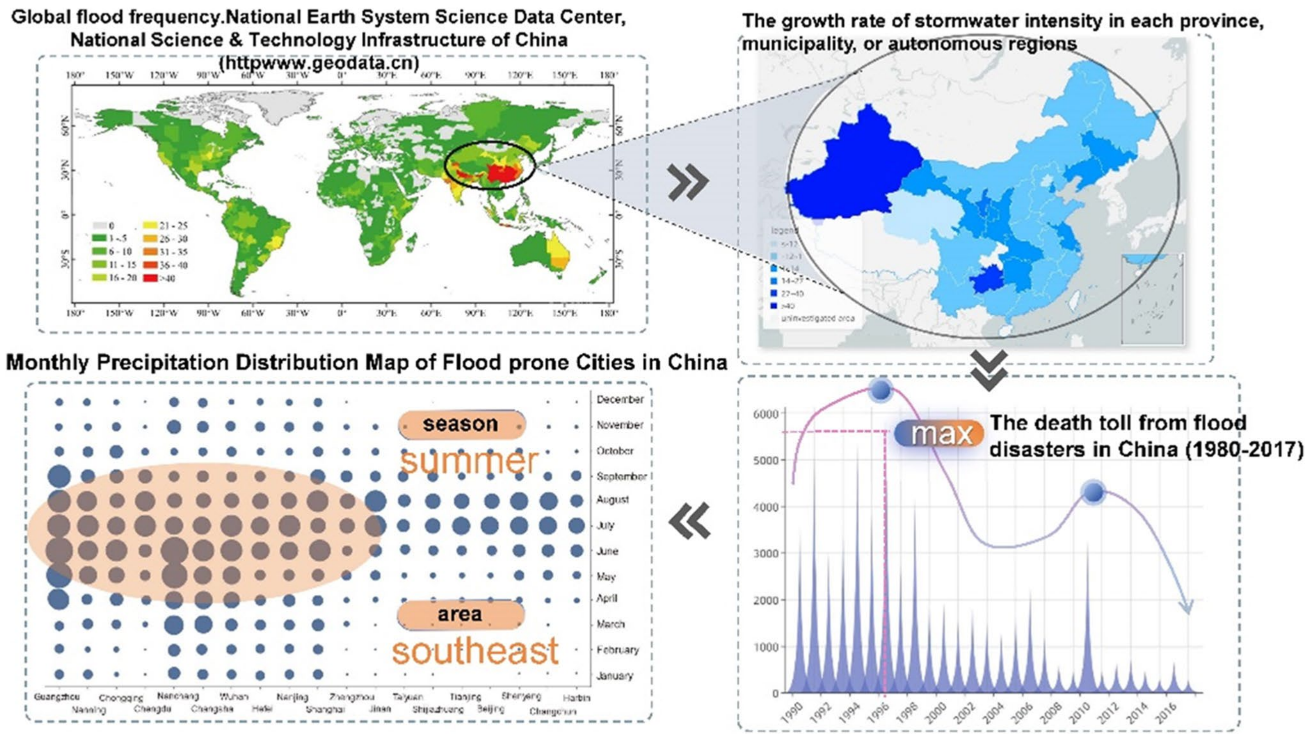


Fig. 2 Characteristics of urban water flooding in China

the river. Consequently, formulating scientifically effective defense measures has become a crucial aspect of urban flood control and drainage.

Analysis of the causes of flooding disasters in China

1. Overexploitation of water resources and lack of water source protection in the process of urbanization

Excessive exploitation of water resources causes over-extraction of groundwater for domestic and industrial purposes, leading to a decline in groundwater levels. Consequently, during rainfall events, surface runoff cannot be promptly absorbed, resulting in surface water flooding. Additionally, the degradation of water resources weakens their protective functions, making cities more vulnerable to extreme weather events. Data indicates a noticeable increase in peak rainfall runoff in urbanized areas compared to pre-urbanization levels, along with frequent occurrences of both drought and flooding in rivers and lakes, as well as a disconnection between parkland and regional water systems. The inability of cities to retain rainwater and replenish groundwater results in increasing surface water levels (Chan et al. 2014).

2. The drainage and heat absorption performance of urban pavement is poor, and the utilization rate of rainwater is low

Due to the high thermal conductivity of the impermeable pavement, it absorbs more solar energy when air pollutants increase; thus, more artificial heat enters the atmosphere. On the other hand, the dense buildings hinder heat dissipation, forming high-temperature centers, known as the "urban heat island effect." Additionally, rigid road surfaces, such as asphalt and concrete, are impermeable and unable to promptly absorb water within the road. Consequently, they generate excessive surface runoff. Furthermore, the design of drainage systems has primarily focused on water disposal rather than rainwater conservation and recycling. As a result, a substantial amount of rainwater remains unutilized, being discharged into the sewer system or natural rivers without being reclaimed.

Key point of "breathe in-breathe out" pavement design in sponge city

The water crisis is a complex and multifaceted problem, which requires a more comprehensive solution. In response to this challenge, the concept of the "sponge city" theory has emerged. As defined by He et al. (2019), a sponge city is analogous to a sponge in its ability to adapt to environmental changes and natural disasters. It absorbs, stores, infiltrates, and purifies water, subsequently releasing and utilizing the stored water as needed, which reduces urban rainwater discharge (Jiang et al. 2018).

At present, over 470 cities in China have launched the construction of sponge cities, with 30 pilot cities having made substantial progress toward achieving their objectives. Notably, these initiatives have significantly enhanced the resilience of cities in coping with flood disasters and have contributed to the improvement and restoration of the ecological environment (Li and Bergen 2018; Fan and Matsumoto 2019; Alam et al. 2019). Among these cases, one of the key points is the usage of porous permeable concrete. Pervious concrete (also known as pervious concrete or porous alpha) is an environmentally friendly material composed of cement, aggregate, and water. It has continuous pores that allow water to pass through, effectively reducing ponding. Permeable concrete pavement serves as a novel method for rainwater treatment, aiming to address the issue of increased surface runoff due to ground hardening and establish a sustainable water cycle by collecting, storing, and reusing natural precipitation. This engineering material with excellent water permeability has demonstrated mitigation effects on urban flooding, effectively reducing and purifying rainwater runoff. Consequently, the application prospects of permeable concrete pavement are vast and warrant further research.

"Breathe in" characteristics of permeable concrete pavement

Pervious concrete pavement type

Structural design

Pervious concrete is formed by coarse aggregate, fine aggregate, binder, admixture, and water resulting in a structure of continuous pores. Permeable concrete pavement is required to withstand both traffic loads and the demands of the urban rainwater system. Therefore, the design of such pavement should consider its hydraulic characteristics (permeability, pore volume) and mechanical properties (compressive strength, flexural strength, etc.). In terms of hydraulic characteristics, factors such as regional annual precipitation, pavement characteristics, and soil foundation characteristics should be comprehensively evaluated (Ismail et al. 2013; Collins et al. 2008). The total runoff is usually less than the total precipitation because some rainfall enters the low-lying areas, some infiltrate into the soil, while others are blocked by the vegetation on the surface. Additionally, different soil types have varying effects on runoff (Bean et al. 2007; Haselbach et al. 2006; Dreelin et al. 2006). Moreover, rainstorm intensity also has a great impact on road runoff, highlighting the significance of permeable concrete pavement design as a vital measure for urban flooding prevention.

Physical properties

Unlike traditional concrete, permeable concrete primarily consists of single-graded coarse aggregate, and its binder is mainly cement mortar or a small amount of fine aggregate mortar. Apart from its protective effect, the cementitious agent should ensure the bonding strength between aggregates and prevent obstruction of the gaps between them. Therefore, the permeability coefficient of permeable concrete is generally between 2.0 and 5.4 mm/s, surpassing that of ordinary concrete. The physical properties of permeable concrete pavement and traditional pavement are compared and analyzed, as shown in Fig. 3.

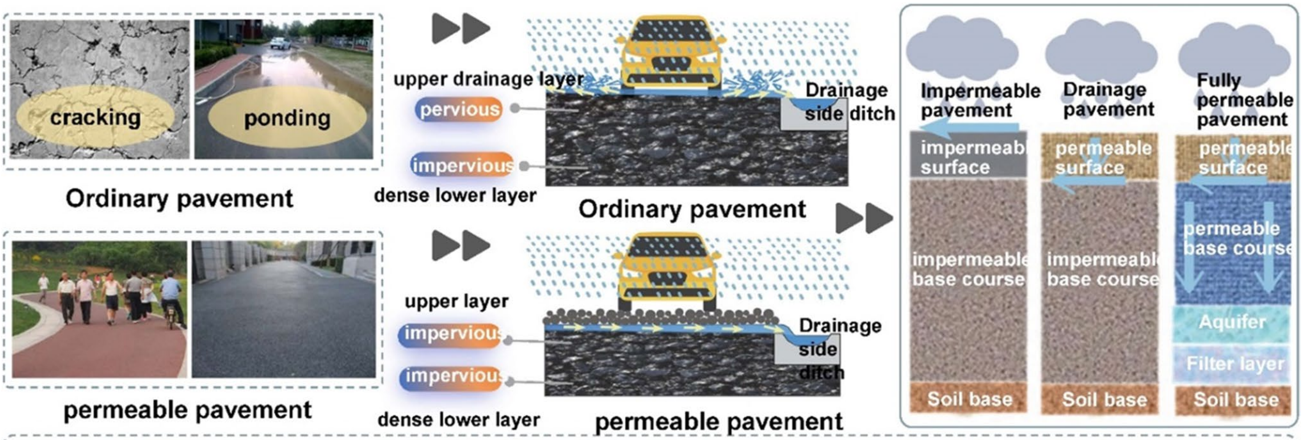
In addition, the physical properties of permeable concrete vary with different influencing factors. As shown in Fig. 4, W/C (the weight ratio of water to cement in concrete) significantly affects the mechanical properties of the concrete. As the W/C ratio increases, the concrete strength decreases. The maximum occurs when W/C = 0.32, while the porosity and permeability show a decreasing trend. Different admixtures have different degrees of influence on the performance of concrete. Test results indicate that ZS-3 has a greater impact, while etonish845 has a lesser impact on concrete strength. At a ratio of 4/2.0, the porosity and permeability coefficient also reach the maximum value respectively. The excessive or insufficient addition of little single-graded crushed stone can reduce the porosity and permeability of concrete. The amount of cement affects the thickness of the cement paste layer and influences concrete performance (Hu et al. 2020; Zhang et al. 2021; Zhang et al. 2018). With the increase in the amount of cement, the porosity and permeability of the specimen decrease.

Analysis of permeable concrete seepage storage capacity

The ability of artificial regulation of residual rainfall on the ground can reduce the risk of floods impacting industrial and agricultural production, as well as people's living environment. The seepage of rainwater directly affects the design of the drainage system inside the road and plays a crucial role in the coupling between the rainwater pipe network and the permeable layer (Chu et al. 2022; Brattebo and Booth 2003). The water storage capacity of permeable pavement directly affects the amount of rainwater that can be absorbed by the site.

1. Different depths of concrete

The variation curve of porosity at different depths is shown in Fig. 5. The experiment compared the differences in permeability rates of pervious concrete specimens at different depths under different flow velocities. In terms of depths of each specimen, it can be observed that the permeability



Pavement Type	Traditional Pavement	Permeable concrete pavement
Disadvantages	1.Blocking rainwater recharge to groundwater 2. Low-lying areas are prone to flooding during heavy rains 3. Easily lead to urban heat island effect 4. Leads to negative environmental and ecological effects	Higher investment
Advantages	Neat, durable and easy to construct	1. Benefit the urban ecosystem 2. Permeable and anti-slip in rainy season and snow in winter 3. Reduce heat island effect 4. Maintain the soil temperature under the road 5. Absorb dust, absorb sound and reduce noise 6. Rich color, more beautiful 7. Reduce urban water pollution
Material composition	Asphalt, cement concrete, impermeable bricks	Porous lightweight cement concrete

Fig. 3 Schematic diagram of pervious concrete effect (Ming et al. 2022; Wang et al. 2017; Nie et al. 2020)

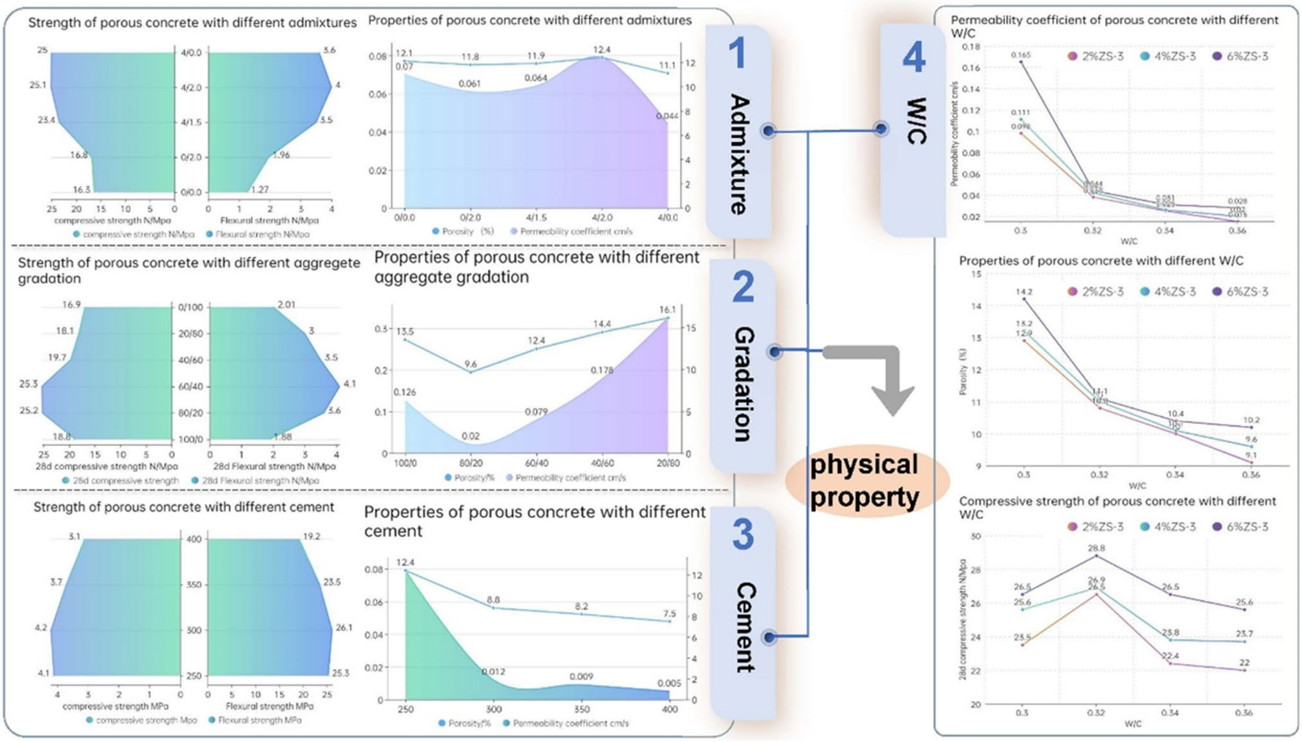


Fig. 4 Variation of physical properties of permeable concrete with different influencing factors (Li et al. 2016)

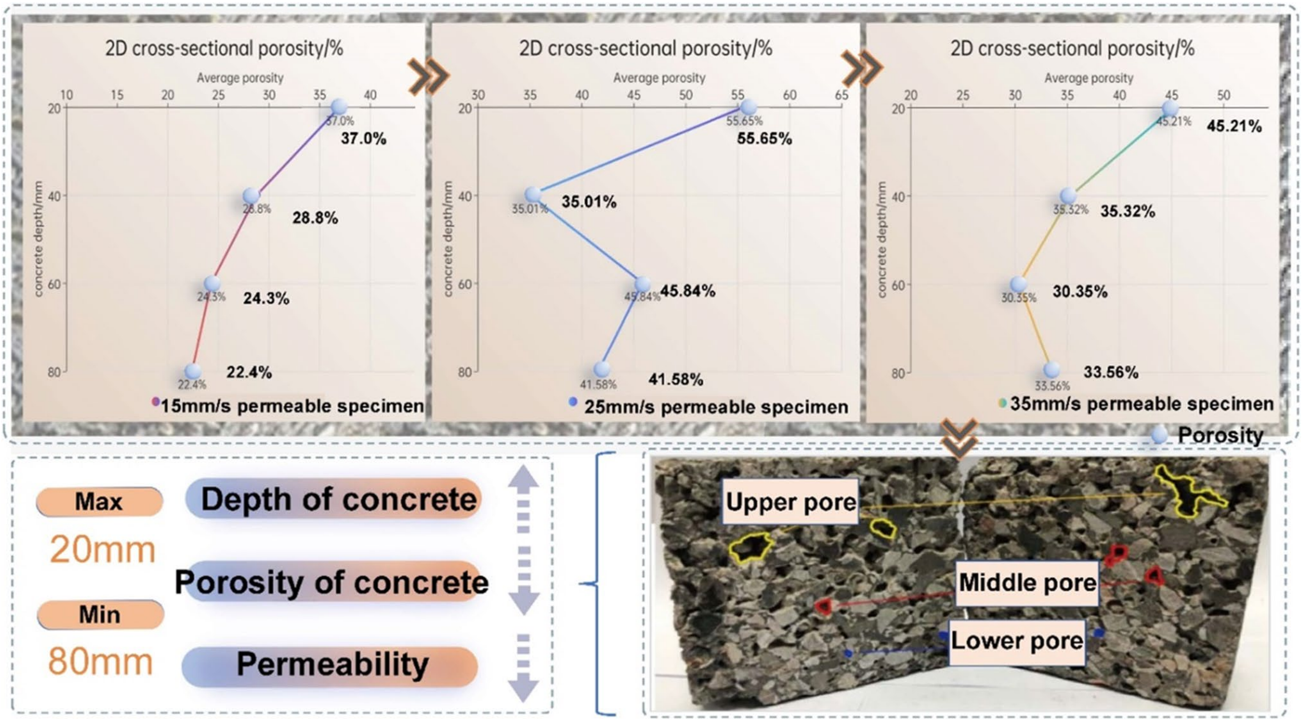


Fig. 5 Infiltration and storage capacity of permeable concrete at different depths (Tan et al. 2021a, b)

is highest at a depth of 20 mm and lowest at a depth of 80 mm. With the increase of the depth, the water permeability gradually decreases, thereby reducing the permeability of the concrete. The results revealed that among the three flow velocities tested, a flow velocity of 25 mm/s had the best permeability performance. This phenomenon can be attributed to the combined effect of the vibration mode and self-weight during the formation of permeable concrete, the continuous rise of bubbles, and the settling of aggregates and cementitious materials.

2. Different rainfall intensities in the region

The dynamic characteristics of rainfall have a significant impact on the seepage volume of permeable pavement. As shown in Fig. 6, the dynamic characteristics of rainfall mainly include rainfall duration, intensity, and intensity (Zhou and Yuan 2022; Xiao et al. 2023; Hou et al. 2022; Chen et al. 2022; Sansalone et al. 2012). With the increase in rainfall intensity, the duration of rainfall increases, as well as the amount of seepage. The drainage system cannot be discharged in time, forming a large amount of surface runoff. In the event of rainstorms, this may also lead to serious ponding within the urban drainage system. Rainfall is closely related to local climate and human activities and is one of the most uncontrollable factors contributing to permeable pavement leakage.

Analysis of plugging factors of permeable concrete

1. Effect of porosity of permeable concrete on plugging

It can be seen from Fig. 7 that the greater the porosity, the easier the permeable concrete is to be blocked. This phenomenon occurs due to the enlargement of pore size and velocity under conditions of high porosity, making particles into the pores during seepage, thereby obstructing the fine channels. On the other hand, in samples with large porosity (e.g., 25% porosity), the permeability coefficient fluctuates considerably after plugging. This is attributed to water flow restarting and facilitating the movement of particles previously blocked within the pores, allowing them to traverse through the pore channels. The analysis below is based on Fig. 7.

2. Effect of storm runoff depth on permeable concrete blockage

It can be seen from Fig. 7 that with the increase of water head height, the likelihood of blockage in permeable concrete also increases. This can be attributed to the combination of high waterhead and permeability rate, making the ingress of a significant number of particles along with the water flow. Thus, the probability of pore blockage is elevated. Consequently, with the increase of road horizontal runoff, permeable concrete pavement is more susceptible to blockage.

3. Effect of plugging material gradation on plugging of permeable concrete

The plugging process of the permeable specimen follows a consistent pattern under the influence of the same plugging material. The permeability reduction caused by fine particle plugging is similar to that caused by fully graded particle plugging because fine sand can easily enter the "throat" of pores. In the specimen with coarse particles, the permeability coefficient is only reduced to approximately 96% before plugging due to the larger particles being likely to block the pore openings on the upper

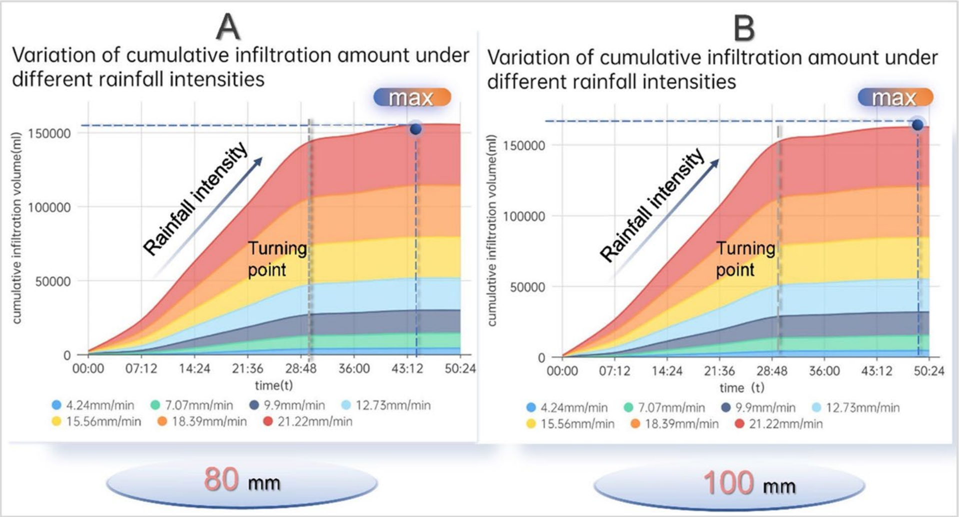


Fig. 6 Infiltration and storage capacity of permeable concrete under different rainfall intensities (Fan 2022)

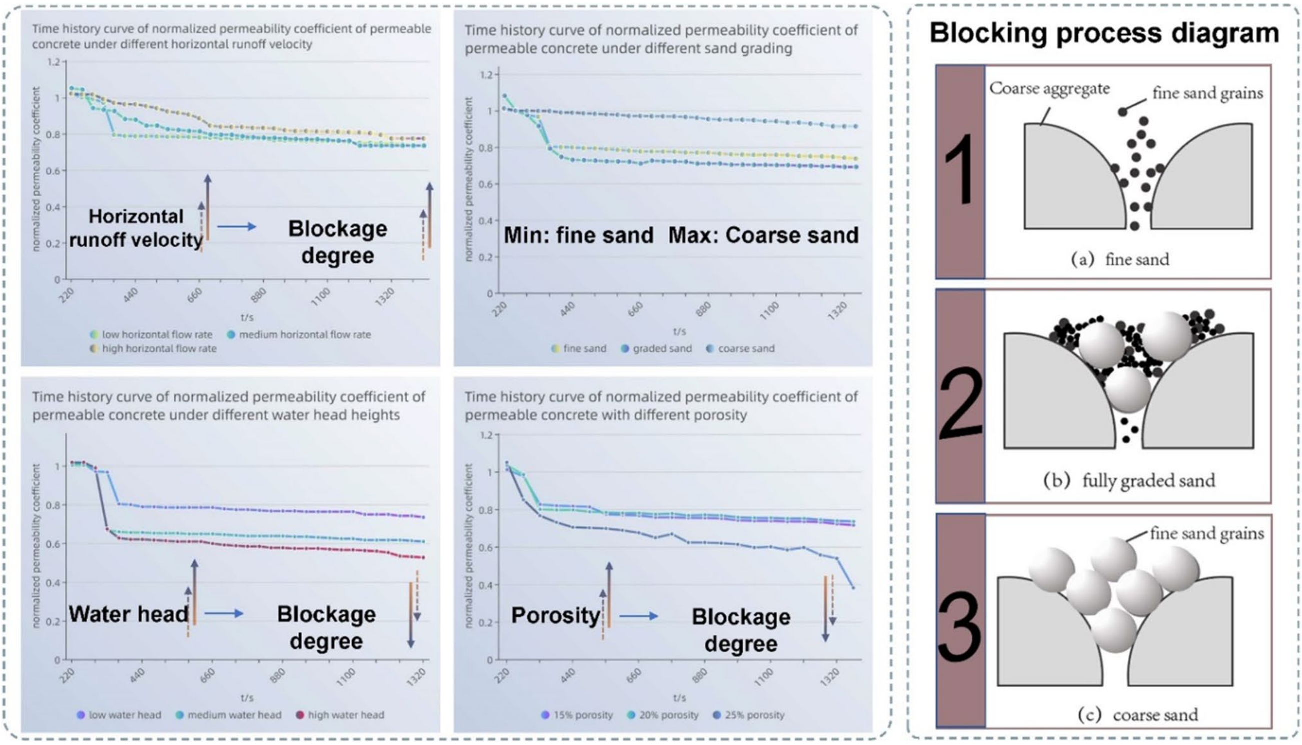


Fig. 7 Influence of different factors on plugging degree of permeable concrete (He et al. 2019)

surface of the sample, making it difficult to penetrate the pore. When the plugging reaches equilibrium, the fully graded sand shows the highest attenuation rate of the permeability coefficient. This is because after the pores in the upper part of the specimen are plugged by the coarser particles, the finer particles are stuck in the remaining gaps, reducing the permeability.

4. Effect of horizontal runoff velocity on permeable concrete blockage

The total mass of the plug in the test specimen remains relatively constant under varying horizontal runoff velocities. At the same time, due to the increase in horizontal runoff velocity, the fine sand particles retained outside the sample will also increase, because the particles will break away from the control of horizontal runoff and gradually penetrate the sample.

In addition, the fitting trend also reveals that the higher permeability coefficient corresponds to the poorer anti-clogging capability of permeable concrete. Consequently, when designing the mix proportion of pervious concrete pavement, the range of the pervious coefficient should ideally fall within the range of 4~8 mm/s, which can not only improve the load resistance of pervious pavement but also meet the pervious demand of pavement.

A case study of Xi'an City

In locations with high construction standards, the selection of permeable pavement as a surface material holds pivotal environmental significance (Yi et al. 2021; Qi et al. 2020). For instance, in a project located on Taichi Street in Beijing, the vehicular lanes of the site were equipped with permeable pavement. The chosen structure type is known as drainage pavement. The design scheme incorporates a permeable asphalt concrete structure for the main vehicle traffic lanes and a permeable cement concrete pavement structure for areas with smaller-scale vehicle traffic. The collected rainwater can be reused nearby, which not only meets the driving demand, but also ensures the comfort of driving and walking, Additionally, this approach reduces water mist during driving, mitigates the heat island effect caused by conventional pavements, and enhances the overall aesthetic appeal of the surroundings (Guan et al. 2021). At the same time, the subsoil type of the site is mainly sandy soil, which has good water retention capability.

Another project is situated in one of the central districts of Xi'an: Yanta district. The project is specifically located at the Yanta campus of Chang'an University, with a population of around 5000, covering a total area of approximately 100,900 m^2. The permeable pavement construction area spans 1200 m^2, accounting for 1.19% of the total area. The precipitation shows uneven variations both inter-annually and seasonally, with rainfall primarily clustered during July to September. The following analysis focuses on the renovation effects of permeable concrete pavement within the region:

1. Total runoff: As shown in Fig. 8, in the simulated rainfall experiment conducted on the site, the rainfall intensities vary from 130 mm/h, 150 mm/h, 170 mm/h, and 200 mm/h; the rainfall durations were set at 45 min and 60 min, with a rainfall time interval of 24 h. Based on the simulated results, the total runoff before the renovation of permeable pavement for different rainfall intensities was 2199.99 m^3, 2611.69 m^3, 3045.98 m^3, and 3684.75 m^3. The total runoff after the renovation was 1076.69 m^3, 1426.16 m^3, 1808.21 m^3, and 2331.15 m^3. The runoff reduction rates were calculated at 51.06%, 45.39%, 40.64%, and 36.74%.
2. Economic benefits: With the application of permeable concrete pavement and permeable plastic pavement, the premised overall expenditure amounted to more than 47 thousand yuan. Based on assumptions, it is estimated that over 10 years, the implementation of permeable pavement can lead to an approximate reduction of 60 thousand yuan in municipal drainage costs, along with rainwater recycling benefits of around 100 thousand yuan, and water quality benefits exceeding 360 thousand yuan (Zhu 2023).

"Breathe out" characteristics of permeable concrete pavement

Heat reduction mechanism of permeable concrete

Urban heat island effect

The heat island effect is a climate phenomenon in which the temperature in the city is higher than that in the peripheral suburbs. In recent years, with urban construction, the heat island effect in China's urban areas has become increasingly obvious. The annual average temperature difference between urban and rural areas is 2–4 °C, and the maximum temperature difference is more than 6 °C (Xia et al. 2017). There are four reasons for the formation of Urban Heat Island:

1. The pavement paved with impermeable materials lacks breathability and the ability to absorb heat and penetrate rainwater. Compared with natural soil, hard pavement has a higher absorption rate of sunlight, and more heat enters the air in the form of damp heat, resulting in air temperature rise (Gunawardena et al. 2017). Dense reinforced concrete buildings and impermeable urban hard pavement have changed the structure of ground evaporation and air humidity, surface albedo and radiation characteristics, ground heat conduction, and heat capacity. For example, when the temperature of the lawn is 32 °C and the temperature under the canopy is 30 °C, the temperature of the cement floor can reach 57 °C, and the

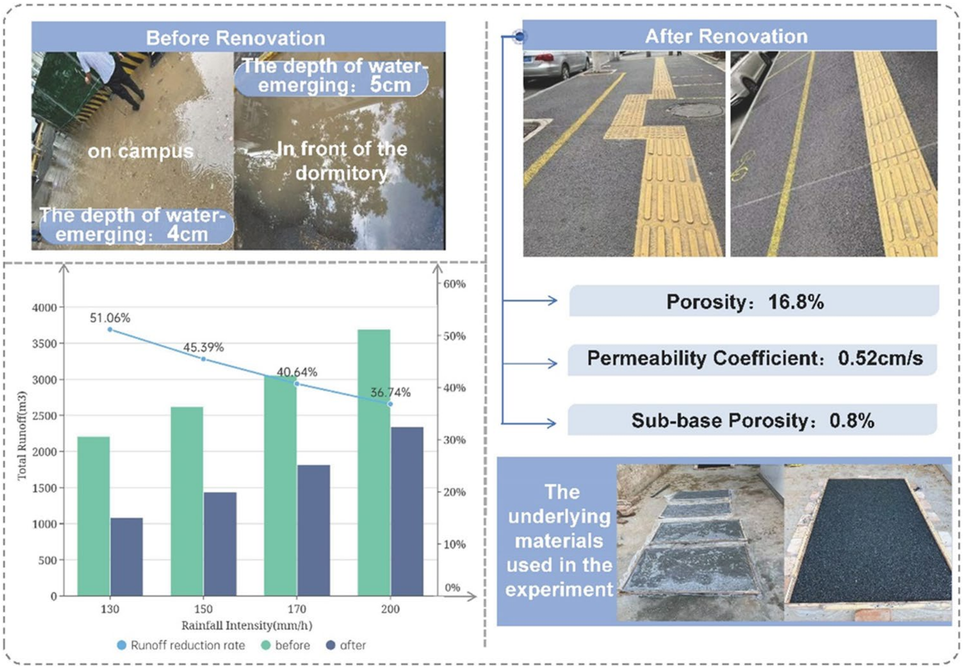


Fig. 8 Comparison of total runoff before and after renovation (Zhu 2023)

temperature of the asphalt road can reach 63 °C (Theeuwes et al. 2013).

2. Motor vehicles, industrial production, and a large number of people's activities in cities produce substantial amounts of nitrogen oxides, carbon dioxide, and dust, among other pollutants. These substances can absorb a large amount of thermal radiation from the environment, leading to greenhouse emissions and extreme climate (Cai et al. 2018).
3. It burns various fuels, consumes a lot of energy, and emits a lot of heat (Wang et al. 2021).
4. The number of buildings, roads, and squares in the city has increased significantly, and the natural environment such as green space and water bodies has been reduced accordingly. The release of heat has intensified, the absorption of heat has diminished, and the capacity to mitigate the heat island effect has been compromised (Abulibdeh 2021).

Cooling effect of permeable concrete pavement

The water storage in the underlying layers of pervious concrete pavement facilitates the evaporation of water under solar radiation, leading to the absorption of a significant amount of heat and subsequent reduction in surface temperatures. Furthermore, the presence of interconnected pores within the pervious concrete allows for efficient heat conduction between the pavement and the subbase, facilitating the dissipation of heat within the pavement structure.

The stored water underground, in the form of water vapor, passes through the pervious pavement and enters the air. This process increases air humidity, promotes air circulation, and carries away heat, resulting in a noticeable decrease in air temperature and an improvement in comfort. Pervious concrete pavement structures thus show a self-regulating ability in terms of surface temperature, making them less susceptible to extreme surface temperatures. After averaging the temperature of three kinds of pavement materials at each test time, Fig. 9 is obtained. The general rule is that the surface temperature increases rapidly with the increase of solar radiation from 8 to 12 o'clock. At 12~ to 16 o'clock, the temperature remained high, and then gradually decreased to a low temperature after 16 o'clock.

Purification mechanism of permeable concrete

Water purification principle

Due to urban construction, automobile exhaust, industrial production, domestic fuel consumption, and other factors, the atmospheric structure with nitrogen compounds as the main pollution source has been formed, and the generation of haze and mist has been greatly accelerated. In addition, the concentration tends to become thicker, the atmospheric transparency

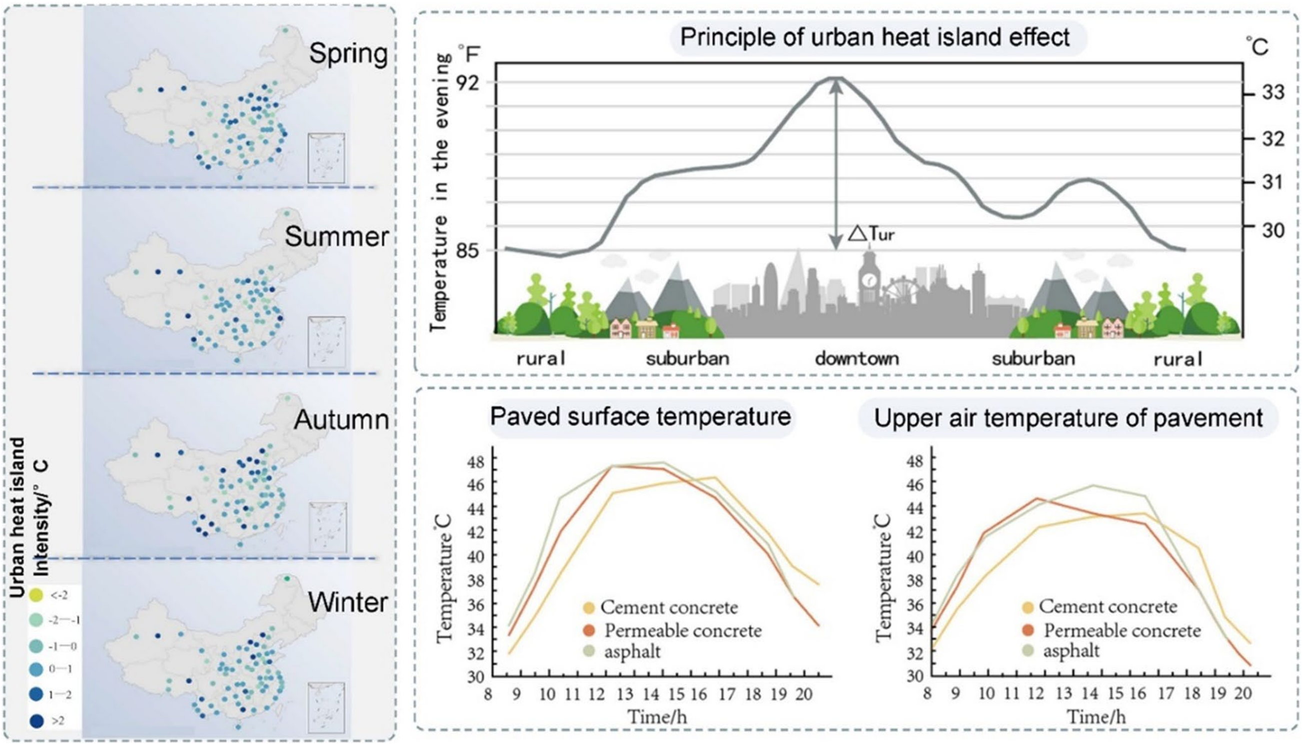


Fig. 9 Intensity of heat island effect and cooling effect of permeable concrete in some cities of China (Hu et al. 2017)

has been reduced, and the sunshine has been reduced. The basic components of permeable concrete have a certain purification effect on pollutants in rainwater runoff. According to Sansalone and Teng (2004), the major components responsible for the purification of Cu^{2+} are aggregate, sand, and cement, with cement playing a crucial role. J.L. Wang also found that cement, quartz sand, and gravel, commonly used materials for pervious concrete pavement, have certain adsorption effects on various typical pollutants (Wang et al., 2017). The study found that cement showed the highest adsorption removal rates for road runoff pollutants, including COD (82%), Cu^2+ (99%), TP (66%), and TN (75%). Quartz sand showed removal rates of 29%, 98%, 56%, and 48% for the same pollutants, while gravel demonstrated rates of 15%, 98%, 66%, and 47%. The comprehensive comparison shows that the adsorption removal effect of cement, quartz sand, and gravel on a copper ion is better than that of other pollutants, and the removal effect of cement on pollutants is the best. The research results show that the purification principle mainly includes the following aspects:

1. Physical adsorption: macroscopically, cement-based materials have a huge specific surface area. According to the calculation, the hydration of 1 cm^3 of cement generates a volume of 2.2 cm^3 of hydrate. With the progress of hydration, the space originally occupied by cement and water is gradually filled with hydration products, while the unfilled voids form irregular pores resulting in a large specific surface area of the concrete matrix after curing so that it can absorb heavy metal ions. Microscopically, relying on the hydration of cement clinker and the pores of hydration products, the crystal morphology of ettringite in cement hydration products and the high dispersion of hydrated calcium silicate gel are conducive to the adsorption of heavy metal ions by cement-based materials (Qi et al. 2021).
2. Double decomposition: after the cement meets with water, each component begins to dissolve, and a hydration reaction occurs to generate Ca (OH) ^{2}. Therefore, the cement remains in an alkaline environment during the hydration process, and the heavy metal ions in the solution can undergo a double decomposition reaction with the OH^- in the cement base to generate precipitation (as shown in formula (1) to formula (4)), to be adsorbed and fixed. The chemical reaction formulas are as follows (Liu et al. 2019):

$$Ca^{2+} + 2OH^- \rightarrow Cu(OH)^2 \downarrow \tag{1}$$

$$Cd^{2+} + 2OH^- \rightarrow Cd(OH)^2 \downarrow \tag{2}$$

$$Zn^{2+} + 2OH^- \rightarrow Zn(OH)^2 \downarrow \tag{3}$$

$$Pb^{2+} + 2OH^- \rightarrow Pb(OH)^2 \downarrow \tag{4}$$

3. Isomorphic displacement: due to the large amount of Ca^{2+}, Al^{3+}, and Mg^{2+} contained in the hydration products of cement can have an isomorphic displacement reaction with the heavy metal ions in the solution so that the heavy metal ions enter the hydration products to achieve the function of adsorption and fixation.

Water purification characteristics of specimens with different voids

It can be seen from the test results in Fig. 10 that there is a strong linear correlation between the design porosity of permeable cement concrete and the pollutant removal rate. The correlation coefficients for these relationships all exceed 93% [55]. Permeable cement concrete can neutralize certain acidity in runoff rainwater and improve the pH value of rainwater. At the same time, it has a certain degree of purification efficacy towards other pollutants. With the increase of the design porosity of permeable cement concrete, the removal rate of pollutants increases gradually, and the pH value increases significantly. Furthermore, the contact surface between the internal voids of concrete and runoff rainwater increases, filtering and adsorbing more pollutants, thereby improving the overall purification effectiveness to a certain extent.

Water purification characteristics of different road materials

The road surface morphology is shown in Fig. 10, following a simulated precipitation test on the permeable cement concrete specimen and open-graded friction course (OGFC) specimen with approximately the same void ratio carried out on the prepared simulated rainwater. The results of the precipitation test reveal the adhesion and interception of suspended solids on the surfaces of both the porous cement concrete pavement and the asphalt concrete pavement. According to the comprehensive analysis of table test results and figures, permeable cement concrete and asphalt concrete have a certain purification effect on pollutants in runoff and rainwater. However, the removal effect of permeable cement concrete is superior to that of asphalt concrete. Furthermore, it is noticeable that the OGFC asphalt mixture has no neutralization effect on H^+ in runoff rainwater and fails to improve the pH value of rainwater.

A case study of Chengde city

Located within the LiuYe Lake scenic area as part of the planning scheme for the LiuYe Lake area in Changde, Hunan Province, the roads between the ground on the western side

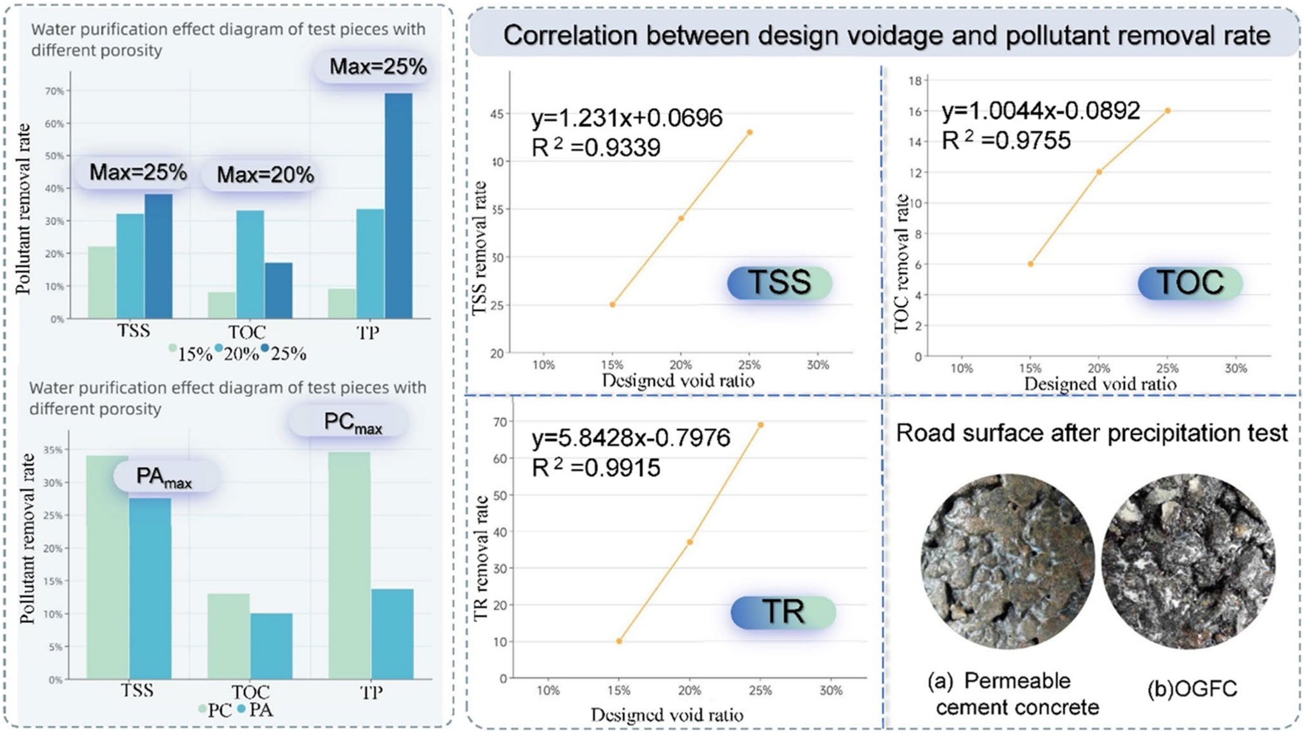


Fig. 10 Water purification effect of permeable concrete. TSS, total suspended solids; TOC, total organic carbon; TP, total phosphorus; PA, drainage asphalt wearing course; PC, permeable cement concrete surface layer (Qin 2017)

are mainly farmland, vegetable fields, lakes, ponds, and a small number of residential houses. The first phase project of Taiyang Avenue is chosen as the focal point. The hydrogeological condition of the construction site is general. The surface water is mainly distributed in low-lying places such as ditches, lakes, and ponds along the road. The water depth is about 1.5 m, and existing more than 20 years. The dominant water source is atmospheric rainfall (Wang and Qu 2017; Qi et al. 2023). Seasonal changes have a prominent impact on water level, subgrade stability, and road foundation construction. The impacts following the transformation are as follows:

1. Road cooling effect. According to the experiment of the project site, the average temperature of ordinary concrete is about 3 T higher than that of permeable cement concrete, while that of asphalt concrete is about 13 °C higher. It can be seen that permeable cement concrete has a significant effect on improving the "heat island effect" of the city. The high porosity of permeable concrete makes the rainwater stored within the material undergo rapid cooling through transpiration. With good air permeability, it can promote water vapor circulation and atmospheric circulation, and regulate environmental temperature and humidity. In addition, the permeable concrete pavement can reduce the pavement temperature by about 5 °C. The use of water vapor evaporated by permeable pavement contributes to an increase in air humidity, thereby effectively mitigating "sand storms" caused by low humidity and ground evaporation (Zhou and Xie 2022; Tan et al. 2021a, b).
2. Pollutant purification effect. The ecological grass planting ditch can store a certain amount of rainwater, slow down the rate of rainwater entering the pipeline ditch, relieve the drainage pressure of the urban pipe network to a certain extent, avoid the occurrence of urban waterlogging in the heavy rain season, and has a significant purification effect combined with permeable concrete (Bao 2019). The usage of biochar permeable concrete effectively reduces the surface runoff before its saturation. Through adsorption and infiltration, the concentration of pollutants is reduced, and urban water pollution is alleviated. Permeable pavement acts as a "purifier" for urban areas and functions as a natural "sewage treatment plant," aligning well with the sustainable development concept of "symbiosis with the environment" (Luo et al. 2019).

Future outlook

Solid waste utilization

In recent years, China's urbanization process has experienced rapid development, leading to a growing scarcity of natural aggregates and other construction raw materials. At the same time, many high-risk buildings with a long history are also facing demolition and reconstruction. Along with many urban construction projects, a substantial amount of construction waste is generated. The recycled coarse aggregate permeable concrete made by crushing and screening can not only solve the disposal of construction waste and agricultural waste but also make full use of resources to improve the mechanical properties and permeability of concrete, which is in line with the concept of "sustainable development."

Colored permeable pavement bricks

Coal gangue and lithium slag are the main industrial wastes in the coal and lithium battery industries respectively. The screened spontaneous combustion coal gangue is used as an aggregate, while lithium slag is used as a mineral admixture. These components are then combined with cement to make colored pavement bricks. Incorporating 5% lithium slag as a substitute for cement greatly reduces the production cost of permeable brick. The permeable surface layer made of inorganic pigment, white cement, and quartz sand can produce permeable brick products with bright colors and excellent performance. It can not only make full use of high emissions of solid waste such as coal gangue and lithium slag but also help the development of China's circular economy. To solve environmental problems, expanding the economic market of resource recycling serves as a new direction.

Luminous permeable concrete pavement

Luminous pervious concrete is a new type of concrete that combines luminous materials and pervious concrete in a certain way. Generally, luminous materials (powder, liquid, block) are mixed with pervious concrete materials. Luminous permeable concrete is environmentally friendly and pollution-free. It absorbs sunlight or light during the day and stores this energy. At night, it slowly releases energy in the form of visible light, which can last for more than 10 h. As shown in Fig. 11, luminous materials offer a diverse range of colors, including green, blue, and red, which can improve the color decoration effect of luminous permeable concrete.

One case is the courtyard dam of the nursing home clinic in Dongyang Town, Beibei District, Chongqing. Initially, the courtyard dam consisted of concrete ground. However, it was transformed into a luminous permeable concrete pavement, featuring intricate designs of "auspicious clouds" and "stars in the sky." After reconstruction, the surface of the courtyard dam is flat, wear-resistant, and anti-skid. The pavement has the following advantages:

1. It has strong adaptability to the elderly and contributes to the construction of therapeutic villages and towns. The permeable pavement with luminescent materials can enhance the illumination of the nursing home at night, especially when the lighting of the courtyard dam is insufficient or even the lighting equipment is damaged, it can play the role of safety warning at night and reduce the occurrence of safety accidents. It can be seen that the luminous permeable concrete pavement can meet the needs of some places without street lights and rural tourism, and help Rural Revitalization and construction.
2. Improve the road environment. It can quickly drain the ponding on the road surface to avoid mirror reflection due to excessive ponding, which will cause driver diz-

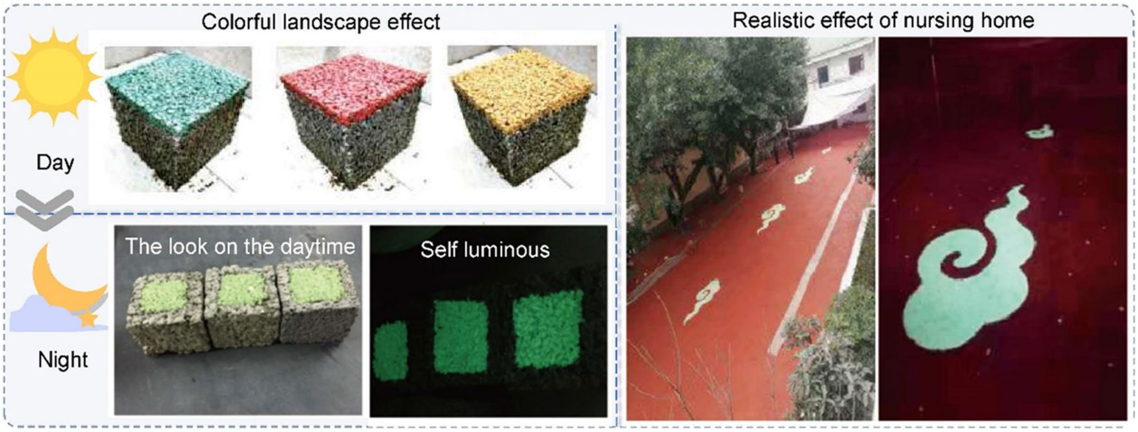


Fig. 11 Effect drawing of luminous permeable concrete (Zheng and Mao 2020; Kong 2020)

ziness, reduce the occurrence of traffic accidents, and facilitate the travel of the elderly. At the same time, porous pavement can absorb vehicle noise and provide residents with a quiet and more comfortable environment.

3. Provide visual beauty. All kinds of luminous patterns are bright during the day and have visual beauty at night. The patterns have cultural connotations and contain good wishes, which can bring visual enjoyment and improve the quality of life for people.

Permeable steel slag concrete pavement

As one of the largest world's steel manufacturing industries, China produces a large amount of waste steel slag every year. However, steel slag can be turned into treasure through processing, and can be used as good road engineering materials after removing harmful substances. Leveraging the high strength and porous characteristics of steel slag, permeable concrete can meet the mechanical structure and drainage function requirements, making it superior to the performance of ordinary permeable concrete (Lai et al. 2022).

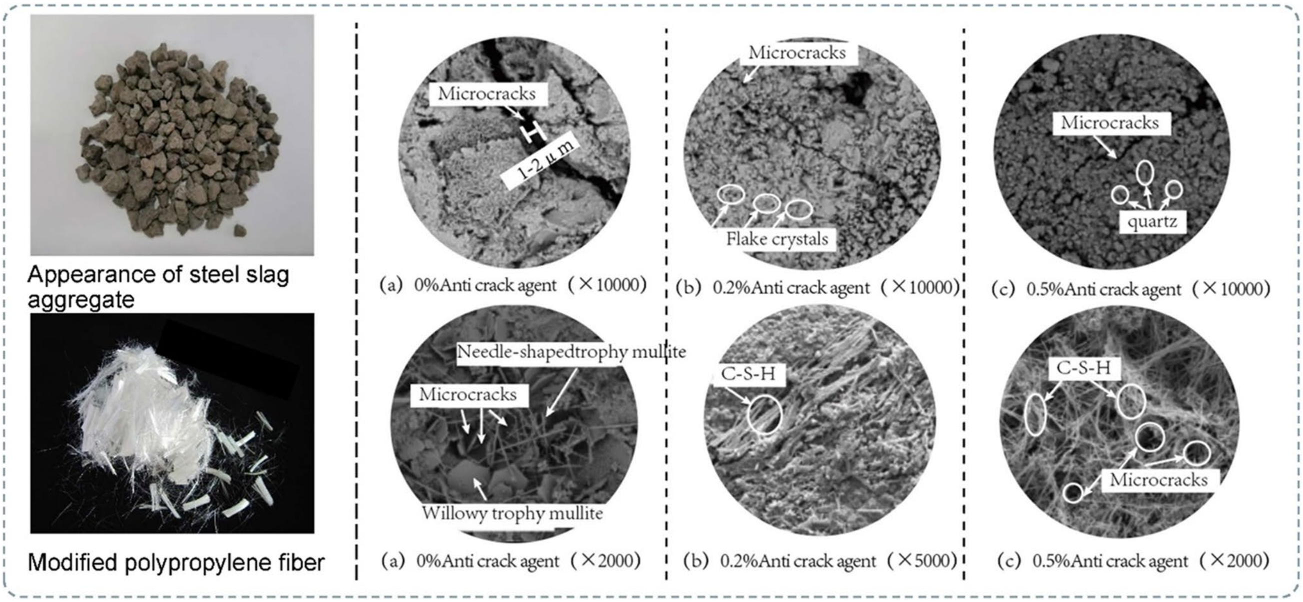
The embankment reinforcement project along the Suzhou section of the Beijing-Hangzhou Grand Canal in Suzhou has implemented the use of permeable steel slag concrete pavement. This pavement offers numerous advantages, including higher load-bearing capacity than normal pavement, wear resistance, a smooth surface, a comfortable walking experience, minimal joints, reduced vibration, low noise levels, and simplified maintenance and repair procedures. Additionally, the cost of raw materials for this pavement is significantly lower compared to conventional non-permeable concrete surfaces, thereby yielding notable ecological and economic benefits.

New material combination

Polypropylene fiber modified polymer permeable concrete pavement

As shown in Fig. 12, polymer pervious concrete is formed by cementing aggregates through resin polymerization and solidification. Its permeability is better than that of ordinary pervious concrete, and the use of polychromatic aggregate enhances its decorative effect (Luo et al. 2019). Polypropylene fiber can effectively enhance its strength, abrasion resistance, impact resistance, and other properties. Furthermore, it reduces the development of brittle damage on the pavement after hardening and improves the durability of the permeable concrete pavement. In this study, ordinary pervious concrete, polymer pervious concrete, and polypropylene fiber-modified polymer pervious concrete were selected to compare their respective runoff reduction effects.

As shown in Fig. 13, polymer pervious concrete shows better resistance to clogging compared to ordinary pervious concrete, mainly because polymer emulsion improves the working performance of fresh pervious concrete and improves the compactness of concrete. In terms of road runoff, the rainfall-runoff coefficient of ordinary pervious concrete pavement ranges from 0.26 to 0.48. Under the same return period and rainfall duration, the runoff coefficient of polymer pervious concrete and polypropylene fiber-modified


Appearance of steel slag aggregate

Modified polypropylene fiber

(a) 0%Anti crack agent (×10000) (b) 0.2%Anti crack agent (×10000) (c) 0.5%Anti crack agent (×10000)

(a) 0%Anti crack agent (×2000) (b) 0.2%Anti crack agent (×5000) (c) 0.5%Anti crack agent (×2000)

Fig. 12 Structure of polypropylene fiber-modified polymer permeable concrete under the electron microscope (Kong 2020)

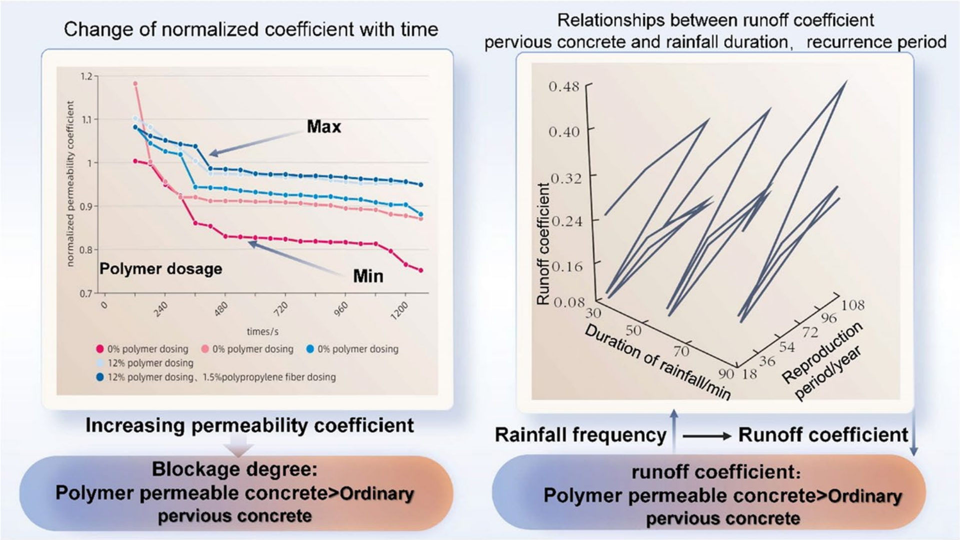


Fig. 13 Effect of polypropylene fiber-modified polymer permeable concrete on runoff reduction (Luo et al. 2019)

polymer pervious concrete is similar but smaller than that of ordinary pervious concrete pavement (Tian 2018). In areas with frequent rainfall events characterized by short durations and short reduction periods, polypropylene fiber-modified polymer pervious concrete pavement has a better runoff reduction effect than ordinary pervious concrete pavement.

Epoxy resin permeable concrete

Epoxy resin permeable concrete is made of a specially graded aggregate, epoxy resin binder, and colorant according to certain mix design methods and preparation processes. Its structure is similar to porous cement concrete, with less or no use of fine aggregate in the grading design process, as shown in Fig. 14. Therefore, the pores are not filled with fine aggregate, resulting in numerous interconnected and semi-connected pores. This phenomenon is attributed to the skeleton pore structure. According to the structural principle of porous cement concrete, the ideal structural model of epoxy resin permeable concrete is shown in the figure below. Comparative analysis of technical performance between common permeable pavement materials and epoxy resin permeable mixtures shows that epoxy resin permeable concrete has obvious advantages in terms of wear resistance, water permeability, frost resistance, colorization, and strength formation time. Compared with permeable cement concrete, its strength formation time is shorter, which can meet the needs of rapid construction in the urban environment.

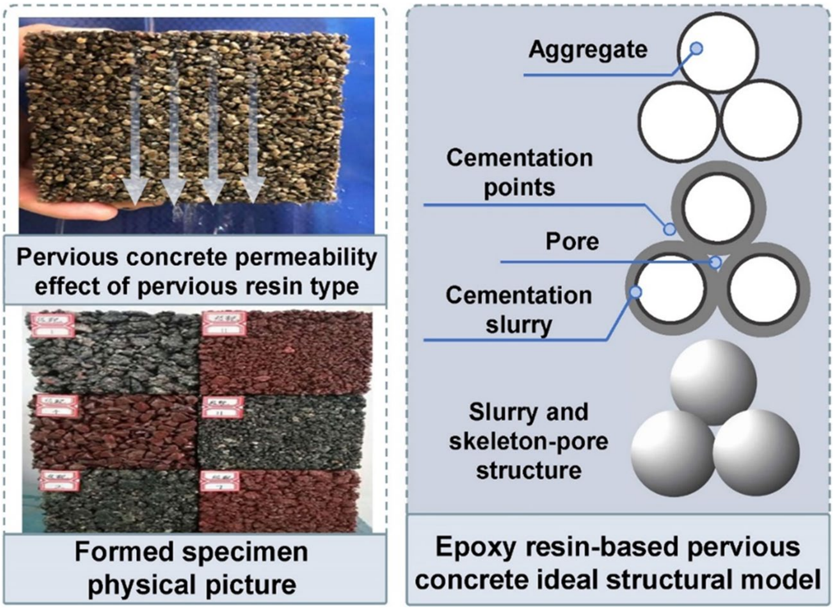


Fig. 14 Epoxy resin pervious concrete structure and pervious effect (Tian 2018)

New design

Application of permeable filter core infiltration well technology in the transformation of sponge city

As shown in Fig. 15, the filter element infiltration well technology is a filter element technology method that uses the existing form as a water storage sponge and embeds a vertical permeable concrete filter in the soil layer. This technology efficiently directs rainwater into the deep soil during rainfall, mitigating disasters and storing water for future use. It is a construction scheme with wide application, low-impact development, and cost-effectiveness. According to the field test and numerical calculation results, the permeable filter infiltration well technology can significantly increase the permeability of the soil itself and can be further applied in the old community, to reduce the surface runoff of the old communities during the rainy season and relieve the pressure of urban flooding, enhance the disaster prevention toughness of these communities, and inject new vitality into the renewal of aging cities.

New tubular permeable structure

The new tubular permeable structure is shown in Fig. 15. Phase a introduces a new tubular double-layer porous structure. A and B (Fig. 16a) are interconnected tubular pores with different diameters, which can not only fully play a protective role, but also ensure the permeability of the permeable structure. C (Fig. 16a) is the solid impermeable skeleton structure. Phase b introduces the movement of clogging particles. Illustrating that the top layer effectively shields sediment particles larger than 1 mm (represented by magenta particles, with Js = 1.18–2.36 mm, and blue particles, with Js = 0.6–1.18 mm) from entering the pores, while allowing smaller sediment particles to freely move within the pores. Phase c introduces the side view of the structure at the end of the coupling. The observation indicates minimal sediment particle retention within the internal pipes of the model, highlighting a significant filtration effect. Moreover, it is evident in phase d that sediment particles larger than the pore diameter of the top layer, which did not enter the pores, can be easily removed. This method effectively closes the pores and prevents the formation of pore throats, reducing the occurrence of plugging. The pore structure of the new tubular double-layer permeable structure features low curvature and uniform diameter sections, facilitating smooth movement of sediment particles within the pores and greatly enhancing the particle transport capacity of the pore structure. Consequently, this new design maximizes the anti-clogging performance of the waterproof structure, minimizes the likelihood of plugging, and extends its effective lifespan.

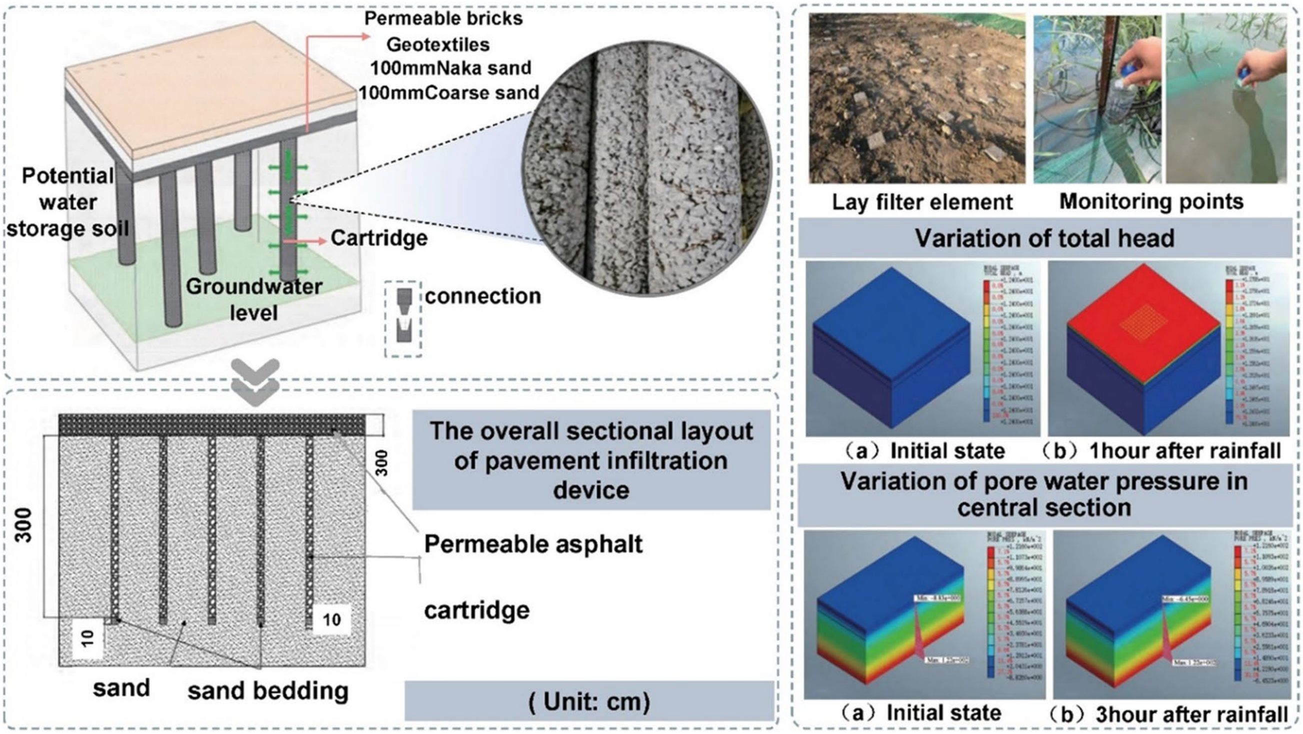


Fig. 15 Pervious filter element structure and pervious effect (Cheng et al. 2021)

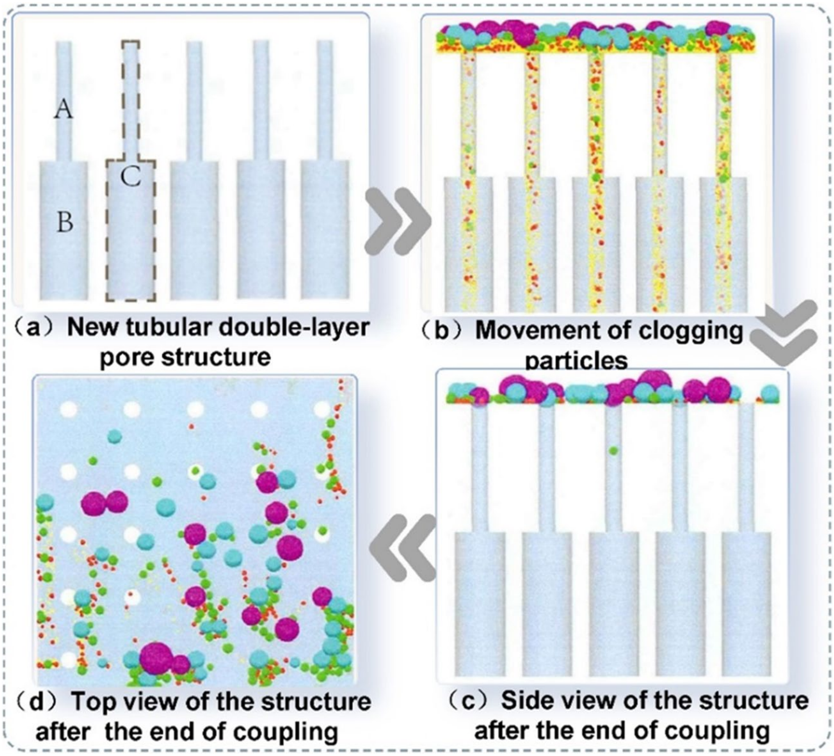


Fig. 16 New tubular permeable structure and permeable principle (Xia 2021)

Conclusions

1. This study discusses the era background and spatial layout of sponge city construction in China. The temporal and spatial characteristics of urban floods in China can be summarized as follows: from the perspective of time, the summer flood cycle is prolonged, and the flood peak is more pronounced. From the perspective of space, it shows the characteristics of "flooding in the South and drought in the North." Additionally, the main reasons for China's urban drainage problems lie in the excessive development of water resources the lack of water source protection in the process of urbanization, and the poor heat absorption performance of urban pavement drainage, which points out that the popularization and use of ecological drainage system is the key to solve the problem of urban drainage.
2. The study focuses on the "breathe in" characteristics of permeable concrete pavement. A brief overview of the various types of pervious concrete pavement is provided, followed by a comparison of the physical properties between ordinary concrete and pervious concrete. Experimental results demonstrate that pervious concrete outperforms ordinary concrete pavement in terms of permeability, compressive strength, and other factors. In terms of infiltration and storage capacity, it is mainly affected by the depth of permeable concrete and regional precipitation intensity. The deeper the depth, the greater the precipitation intensity, the smaller the amount of infiltration and storage, and the greater the amount of seepage. In addition, the plugging factors of permeable concrete are analyzed. They are revealing that higher porosity increases the susceptibility to clogging. The blocking tendency of permeable concrete is influenced by the depth of storm runoff, the higher the water head is, the more easily the permeable concrete is blocked. Finally, the analysis of plugging materials' gradation reveals that coarse sand results in a higher degree of clogging compared to fine sand and fully graded sand.
3. The "breathe out" characteristics of permeable concrete pavement are investigated in this study. Comparative tests reveal that from 8 to 12 o'clock, permeable concrete pavement reduces the temperature by approximately 1 °C compared to cement concrete. Furthermore, from 12 to 20 o'clock, the cooling effect becomes more pronounced, with a temperature difference of around 3 °C near the surface. These findings indicate that permeable concrete reduces the pavement temperature more significantly compared to cement pavement, thus mitigating the urban heat island effect. Moreover, the chemical mechanism underlying the ability of permeable concrete to adsorb impurities and purify water is analyzed. Macroscopically, physical adsorption occurs, while microscopically, double decomposition and isomorphic replacement reactions take place between impurities and the concrete, facilitating the removal of impurities. This

showcases the favorable environmental utility of permeable concrete pavement.

4. The innovation and development direction of permeable concrete in sponge city construction are summarized. This paper focuses on three research directions: solid waste utilization, new material combination, and new design. These directions involve integrating pervious concrete with resource reuse, employing specialized materials, and implementing novel structural designs, thereby demonstrating its immense application potential and promising development prospects.

Author contribution Yu Huang: investigation, data curation, and writing. Hao Sun: conceptualization, methodology, funding acquisition, supervision, and review. Yuhang Liu: data curation, investigation, and validation. Kai Zhao: literature, investigation, and validation. Tong Liu: investigation. Dedi Liu: data curation.

Funding This work is financially supported by the Natural Science Basic Research Program of Shaanxi Province (Youth Project) (2024JC-YBQN-0519) and the Humanities and Social Science Fund of the Ministry of Education of China (22YJC760134).

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abulibdeh A (2021) Analysis of urban heat island characteristics and mitigation strategies for eight arid and semi-arid gulf region cities. Environ Earth Sci 80:259. https://doi.org/10.1007/s12665-021-09540-7

Alam T, Mahmoud A, Jones KD, Bezares-Cruz JC, Guerrero J (2019) A Comparison of three types of permeable pavements for urban runoff mitigation in the semi-arid south Texas. Water 11:1992. https://doi.org/10.3390/w11101992

Bao MP (2019) Wrap wooden flat research on the control effect of rainwater runoff and pollutant reduction effect of four different structural permeable surfaces. Xi’an University of Architecture and Technology

Bean EZ, Hunt WF, Bidelspach DA (2007) Field survey of permeable pavement surface infiltration rates. J Irrig Drain Eng 133:249–255. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:3(249)

Brattebo BO, Booth DB (2003) Long-term stormwater quantity and quality performance of permeable pavement systems. Water Res 37:4369–4376. https://doi.org/10.1016/S0043-1354(03)00410-X

Cai Z, Han G, Chen MC (2018) Do water bodies play an important role in the relationship between urban form and land surface temperature. Sustain Cities Soc 39:487–498. https://doi.org/10.1016/j.scs.2018.02.033

Chan FKS, Wright N, Cheng X, Griffiths J (2014) After sandy: rethinking flood risk management in Asian coastal megacities. Natural Hazards Review 15:101–103. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000117

Chan FKS, Griffiths JA, Higgitt D, Xu SY, Zhu FF, Tang YT, Xu YY, Thorne CR (2018) “Sponge City” in China breakthrough of planning and flood risk management in the urban context. Land Use Policy 76:772–778. https://doi.org/10.1016/j.landusepol.2018.03.005

Chen X, Yang Y, Zhang C, Hui R, Zhang HY, Li BX, Zhao QL (2022) Valorization of construction waste materials for pavements of sponge cities: a review. Constr Build Mater 356:129247. https://doi.org/10.1016/j.conbuildmat.2022.129247

Cheng XL, Liu Y, Hai R, Li SQ (2021) Research on permeable filter infiltration technology and its application in urban sponge transformation. Water Conservancy and Hydropower Technology (Chinese and English) 52:66–75. https://doi.org/10.13928/j.cnki.wrahe.2021.08.007

Chu XX, Campos-Guereta I, Dawson A, Thom N (2022) Sustainable pavement drainage systems: subgrade moisture, subsurface drainage methods and drainage effectiveness. Constr Build Mater 364:129950. https://doi.org/10.1016/j.conbuildmat.2022.129950

Collins KA, Hunt WF, Hathaway JM (2008) Hydrologic comparison of four types of permeable pavement and standard asphalt in Eastern North Carolina. J Hydrol Eng 13:1146–1157. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:12(1146)

Cui HH, Li R, Gao YN, Li N, Wang SB (2023) Study on the precipitation details and disaster formation process of “7·20” Extreme Rainstorm in Zhengzhou. Journal of Catastrophology 38:114–120+149 https://link.cnki.net/urlid/61.1097.P.20230202.0956.001

Dreelin EA, Fowler L, Carroll CR (2006) A test of porous pavement effectiveness on clay soils during natural storm events. Water Res 40:799–805. https://doi.org/10.1016/j.watres.2005.12.002

Fan H (2022) Research on the application of permeable concrete pavement seepage storage and coupling with rainwater pipe network. Xi’an University of Architecture and Technology. https://doi.org/10.27393/d.cnki.gxazu.2021.000727

Fan XZ, Matsumoto T (2019) GIS-based social cost-benefit analysis on integrated urban water management in China: a case study of Sponge City in Harbin. Sustainability 11:5527. https://doi.org/10.3390/su11195527

Guan X, Wang J, Xiao F (2021) Sponge city strategy and application of pavement materials in sponge city. J Clean Prod 303:127022. https://doi.org/10.1016/j.jclepro.2021.127022

Gunawardena KR, Well SMJ, Kershaw T (2017) Utilising green and blue space to mitigate urban heat island intensity. Sci Total Environ 584-585:1040–1055. https://doi.org/10.1016/j.scitotenv.2017.01.158

Haselbach LM, Valavala S, Montes F (2006) Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems. J Environ Manag 81(1):42–49. https://doi.org/10.1016/j.jenvman.2005.09.019

He BJ, Zhu J, Zhao DX, Gou ZH, Qi JD, Wang JS (2019) Co-benefits approach: opportunities for implementing sponge city and urban heat island mitigation. Land Use Policy 86:147–157. https://doi.org/10.1016/j.landusepol.2019.05.003

Hou JM, Dong MJ, Li DL, Ma Y, Ji GQ, Zhang S (2022) Drainage effect of urban rainwater pipe network under excessive rainstorm-take Fengxi New Town in Xi’an as an example. J Earth Sci Environ 45:1–10 https://kns.cnki.net/kcms/detail/61.1423.P.20220906.1637.001.html

Hu J, Yao Y, He YL, Chen DG, Fu DS (2017) Experimental study on reducing heat island effect of permeable concrete integral pavement. Green Building 9(1):69–72. https://doi.org/10.3969/j.issn.1004-1672.2017.01.020

Hu N, Zhang J, Xia S, Han RN, Dai ZX, She R, Cui XZ, Meng BW (2020) A field performance evaluation of the periodic maintenance for pervious concrete pavement. J Clean Prod 263:121463. https://doi.org/10.1016/j.jclepro.2020.121463

Ismail I, Bernal SA, Provis JL, Nicolas RS, Brice DG, Kilcullen AR, Hamdan S, van Deventer JS (2013) Influence of fly ash on the water and chloride permeability of alkali-activated slag mortars and concretes. Constr Build Mater 48:1187–1201. https://doi.org/10.1016/j.conbuildmat.2013.07.106

Jiang Y, Chris Z, Ma YC (2018) Urban pluvial flooding and stormwater management: a contemporary review of China's challenges and "sponge cities" strategy. Environ Sci Pol 80:132–143. https://doi.org/10.1016/j.envsci.2017.11.016

Kong DY (2020) Research on the application of permeable steel slag concrete pavement in sponge city construction. Southeast University: 1-99. https://doi.org/10.27014/d.cnki.gdnau.2020.002609

Lai MH, Chen ZH, Wang YH, Ho JCM (2022) Effect of fillers on the mechanical properties and durability of steel slag concrete. Constr Build Mater 335:127495. https://doi.org/10.1016/j.conbuildmat.2022.127495

Li L, Bergen JM (2018) Green infrastructure for sustainable urban water management: practices of five forerunner cities. Cities 74:126–133. https://doi.org/10.1016/j.cities.2017.11.013

Li YC, Lu CH, Liu RG, Xu RJ, Wen HQ, Gong JH (2016) Analysis of porous concrete on lighten road. Bulletin of the Chinese Ceramic Society 35:3132–3138. https://doi.org/10.16552/j.cnki.issn1001-1625.2016.10.008

Liu WW, Ma KL, Zhang CQ, Long GC, Xie YJ, Bian W (2019) Research progress on purification mechanism of pollutants in urban stormwater runoff by pervious concrete. Materials Report 33:293–299

Luo WG, Qian X, Lu GW, Xiao Y (2019) Road performance test of polypropylene fiber modified polymer permeable concrete pavement. Journal of Building Science and Engineering 35:118–126. https://doi.org/10.3969/j.issn.1673-2049.2018.06.016

Ming RP, Xie AL, Zhang YJ, Zhang J (2022) Study on strength and permeability of pervious concrete. Concrete 4:147–153

Ministry of Water Resources of the PRC (2023) Annual report on China's water resources 2022. China Water & Power Press, Beijing

Nguyen T, Ngo H, Guo W, Wang X, Ren N, Li G, Ding J, Liang H (2019) Implementation of specific urban water management - Sponge City. Sci Total Environ 652:147–162. https://doi.org/10.1016/j.scitotenv.2018.10.168

Nie HY, Wang WL, Guo MM, Kang HL, Li JM, Bai Y (2020) Runoff-sediment relationship and erosion dynamic characteristics for two types of engineering deposits under rainfall conditions. Chin J Appl Ecol 31:3141–3153. https://doi.org/10.13287/j.1001-9332.202009.013

Qi XY, Zhang SH, Wang YJ, Li MY, Jiang YC, Wang RCY, Jiang YZ, Ma XY (2020) Impacts of particle size and maintenance on clogging processes of permeable pavement systems. Environ Sci Technol 43(08):28–35. https://doi.org/10.19672/j.cnki.1003-6504.2020.08.005

Qi Y J， Kang A H, Lu Z P, Kou C J, Xu X L (2021) Permeability and purification ability of permeable asphalt mixture under two simulated conditions. J Mater Sci Eng 39: 124-129. https://doi.org/10.14136/j.cnki.issn1673-2812.2021.01.021

Qi B, Gao S, Xu P (2023) The application of rubber aggregate-combined permeable concrete mixture in sponge city construction. Coatings 13:87. https://doi.org/10.3390/coatings13010087

Qin X (2017) Research on pavement performance and water purification characteristics of permeable concrete pavement and cement stabilized macadam base based on sponge city. Chongqing Jiaotong University, pp 1–103. https://doi.org/10.7666/d.Y3225457

Qiu JL, Liu DD, Zhao K, Lai JX, Wang XL, Wang ZC, Liu T (2024a) Influence spatial behavior of surface cracks and prospects for prevention methods in shallow loess tunnels in China. Tunnelling and Underground Space Technology 143:105453. https://doi.org/10.1016/j.tust.2023.105453

Qiu JL, Liu YH, Qian XY, Ma C, Liu J, Liu T, Han HX (2024b) Guarantee rate statistics and product-moment correlation analysis of the optimal deformation allowance for loess tunnel in China. Environ Earth Sci 83. https://doi.org/10.1007/s12665-023-11263-w

Sansalone J, Teng Z (2004) In situ partial exfiltration of rainfall-runoff I: quality and quantity attenuation. J Environ Eng 130:990–1007. https://doi.org/10.1061/(ASCE)0733-9372(2004)130:9(990)

Sansalone J, Kuang X, Ranieri V (2012) Filtration and clogging of permeable pavement loaded by urban drainage. Water Res 46:6763–6774. https://doi.org/10.1016/j.watres.2011.10.018

Sarkar SK, Rahman MA, Esraz-Ul-Zannat M, Islam MF (2021) Simulation-based modeling of urban waterlogging in Khulna City. Journal of Water and Climate Change 12:566–579. https://doi.org/10.2166/wcc.2020.256

Stanczuk-Galwiaczek M, Sobolewska-Mikulska K, Ritzema H, van Loon-Steensma JM (2018) Integration of water management and land consolidation in rural areas to adapt to climate change: experiences from Poland and the Netherlands. Land Use Policy 77:498–511. https://doi.org/10.1016/j.landusepol.2018.06.005

Tan KH, Wang TY, Zhou ZH (2021a) Biochar as a partial cement replacement material for developing sustainable concrete: an overview. J Mater Civ Eng 33:03121001. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003987

Tan Y, Yi CG, Andy H, Xiao HL (2021b) Experimental study on blocking and permeability recovery of permeable concrete pavement. Journal of Central South University (Natural Science Edition) 52:2480–2490. https://doi.org/10.11817/j.issn.1672-7207.2021.07.033

Tang K, Liu D, Xie S, Qiu J, Lai J, Liu T, Fang Y (2024) Analysis of loess water migration regularity and failure response of tunnel structure under rainfall environment. Bull Eng Geol Environ 83(6):1–22. https://doi.org/10.1007/s10064-024-03715-9

Theeuwes NE, Solcero VA, Steeneveld GJ (2013) Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. J Geophys Res-Atmos 118:8881–8896. https://doi.org/10.1002/jgrd.50704

Tian PJ (2018) Composition design and performance study of epoxy resin concrete permeable pavement materials. Chang'an University: 1–89

Uribe CHA, Brenes RB, Hack J (2022) The potential of retrofitted urban green infrastructure to reduce runoff-A model implementation with site-specific constraints at the neighborhood scale. Urban For Urban Green 69:127499. https://doi.org/10.1016/j.ufug.2022.127499

Wang XY, Qu LY (2017) Application of pervious concrete pavement in Beijing municipal road engineering. Urban Roads and Bridges and Flood Control 12:185–187. https://doi.org/10.3969/j.issn.1002-3550.2022.04.031

Wang JL, Zhang HY, Sheng W, Zhang YJ, Feng CM, Li JQ (2017a) Experimental study on runoff and pollutant reduction conducted bypervious concrete pavement under extreme rainfall. Environ Eng 35:28–32. https://doi.org/10.13205/j.hjgc.201702007

Wang K, Zhang H, Chen Y (2017b) Analysis of COD design method for combination of traffic and water in sponge city based on the urban design of Yangming Lake area in Changde. Hunan Province Architecture & Culture 163:198–201. https://doi.org/10.3969/j.issn.1672-4909.2017.10.080

Wang X J， Dallimer M, Scott C E, Shi W T, Gao J X (2021) Tree species-richness and diversity predicts the magnitude of urban heat island mitigation effects of green spaces. Sci Total Environ 770: 145211, https://doi.org/10.1016/j.scitotenv.2021.145211

Wu FT, Fu CB (2013) Change of precipitation intensity spectra at different spatial scales under warming conditions. Chin Sci Bull 58:1385–1394. https://doi.org/10.1007/s11434-013-5699-0

Xia S (2021) Summer frost optimization of the anti-clogging performance of permeable pavement structure. Shandong University: 1–80. https://doi.org/10.27272/d.cnki.gshdu.2021.003608

Xia J, Zhang YY, Xiong LH, He S, Wang LF, Yu ZB (2017) Opportunities and challenges of the Sponge City construction related to urban water issues in China. Sci China Earth Sci 60:652–658. https://doi.org/10.1007/s11430-016-0111-8

Xiao S, Zou L, Xia J, Dong Y, Yang Z, Yao T (2023) Assessment of the urban waterlogging resilience and identification of its driving factors: a case study of Wuhan City, China. Sci Total Environ 866:161321. https://doi.org/10.1016/j.scitotenv.2022.161321

Yi SJ, Kou JY, Du WG, Zhang G (2021) Research progress of permeable concrete pavement. China Science and Technology Information 07:59–60. https://doi.org/10.3969/j.issn.1001-8972.2021.07.020

Zhang Q, Zheng YJ, Singh VP, Luo M, Xie ZH (2017) Summer extreme precipitation in eastern China: mechanisms and impacts. J Geophys Res Atmos 122:2766–2778. https://doi.org/10.1002/2016JD025913

Zhang J, Ma GD, Dai ZX, Ming RP, Cui XZ, She R (2018) Numerical study on pore-clogging mechanism in pervious pavements. J Hydrol 565:589–598. https://doi.org/10.1016/j.jhydrol.2018.08.072

Zhang J, Xia S, Hu N, Hao W, Han R, Meng B, Zhang Z (2021) Optimization of anti-clogging pervious pavement structure based on numerical evaluation. Constr Build Mater 275:122186. https://doi.org/10.1016/j.conbuildmat.2020.122186

Zheng C, Mao YZ (2020) Research on the preparation technology of color permeable concrete pavement brick based on solving the environmental pollution problem of solid waste. Energy conservation and environmental protection 07:72–73. https://doi.org/10.3969/j.issn.1009-539X.2020.07.030

Zhou MJ, Yuan HL (2022) Research on growth rate of rainstorm intensity and urbanization impact in some cities of China. China Water Supply and Drainage 38:126–131. https://doi.org/10.19853/j.zgjsps.1000-4602.2022.19.020

Zhou ZH, Xie JL (2022) Numerical analysis on the optimization of evaporative cooling performance for permeable pavements. Sustainability 14:4915. https://doi.org/10.3390/su14094915

Zhu SW (2023) Experimental study on two types of permeable pavement flow generation mechanisms and simulation analysis of their application in northern cities. Changan University: 1–91. https://doi.org/10.26976/d.cnki.gchau.2023.002441