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Cooling and purification effect of permeable pavements

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ABSTRACT

Permeable pavement is a widely used stormwater runoff blocking technology in sponge city construction. Its application to urban motorized/non-motorized roads is expected to reduce runoff and pollution loads. This study aimed to analyze the nutrient pollution, thermal pollution reduction efficiency and removal pathways of cement permeable bricks (CP-B-Cement), steel slag permeable bricks (SP-B), ceramic permeable bricks (CP-B-Ceramic) and permeable asphalt pavement (PAP) under different pollution loads and rainfall intensities by simulating the different stormwater runoffs. Results indicated that the effluent concentration of different permeable pavements increased with the extension of rainfall duration. Compared with impermeable pavements, the infiltration and water storage capacities of permeable pavements could effectively remove typical pollutants from stormwater runoff. However, the effluent concentrations of all pollutants did not reach the threshold of Class V according to the *Environmental Quality Standards for Surface Water* except for TP and Zn. Meanwhile, the thermal pollution removal capacity of the permeable pavements ranking from the highest to the lowest was SP-B > CP-B-Cement > CP-B-Ceramic > PAP. The findings in this study provide references for the selection of stormwater source reduction facilities and the development of surface source pollution countermeasures.

Key words: cooling, permeable pavements, purification efficiency, sponge city, stormwater runoff

HIGHLIGHTS

- The nexus of urban cooling and water purification effects of permeable materials.
- Four types of new materials including cement permeable bricks (CP-B-Cement), steel slag permeable bricks (SP-B), ceramic permeable bricks (CP-B-Ceramic) and permeable asphalt pavement (PAP) were investigated.
- The effluent concentration of different permeable pavements increased with the extension of rainfall duration.

1. INTRODUCTION

Rapid urbanization and the expansion of impervious areas have led to increasing urban flooding risks and runoff pollution problems (Qi *et al.* 2019; Ferrari *et al.* 2020). Urban stormwater runoff has not only contained pollutants such as suspended solids (SS), heavy metals, organic matter, total nitrogen (TN) and total phosphorus (TP) (Wang *et al.* 2015; Wu *et al.* 2015), but there has also been thermal pollution of water bodies caused by high-temperature stormwater runoff discharged into receiving water bodies (Li *et al.* 2020), resulting in lower dissolved oxygen concentrations, higher nitrogen and phosphorus concentrations, and massive aquatic-animal die-off from hypoxia, which has endangered the health of rivers and lakes and damaged water ecosystems (Xu *et al.* 2020a, 2020b, 2020c). Flooding could significantly raise the moisture content of materials in pavements to saturation, which is known to degrade the mechanical qualities of most paving materials (Awwad 2021; Nawir & Mansur 2022). Therefore, the study of pollutant removal and heat reduction in the initial runoff of pavement is very important for the environmental health assessment of surface water and ecological protection of river water in China. To manage stormwater problems in cities, various technical measures have been widely developed, including the Low Impact Development concept (LID) in the United States (Mohajerani *et al.* 2017), the Sustainable Drainage Concept (SUDS) in the United Kingdom (Mbanaso *et al.* 2019), Water Sensitive Urban Design (WSUD) in Australia (Morison &

Brown 2011), the ABC Water Program in Singapore (Hopkins *et al.* 2018) and the Sponge City in China (Barbosa *et al.* 2012). Permeable pavement is a common LID technology with an open void structure in different structural layers that enables continuous infiltration of rainwater, cutting the effluent temperature by 4.4–5.2 °C (Xu *et al.* 2020a, 2020b, 2020c), and is easy to maintain, repair and renovate as a source control measure without occupying urban landscape space.

The permeable pavement is a paving technology based on full infiltration, including permeable surface layer, gravel base layer, geotextile and bedding layer (Guan *et al.* 2021). When generating heavy rainfall, rainwater first infiltrates into the pavement storage area and then discharges into rivers or infiltrates into the surrounding soil through catchment pipes and eventually into groundwater, which plays an important role in water quality and quantity regulation and maintains the stability of water ecosystems (Martins Vaz *et al.* 2020; Winston *et al.* 2020). It has been shown (Liu & Borst 2018) that permeable pavements are more effective in removing pollutants attached to suspended solid particles (Pb, Al, Fe, N and P) than dissolved pollutants (Cu, Zn and Mn), and the content of Na, K and V in the effluent of permeable concrete pavement (PC) is significantly higher than that of permeable asphalt pavement (PAP) and permeable brick pavement (PICP) and the reduction rates of stormwater runoff for different types of permeable pavement runoff reduction rates correlate well with rainfall intensity (Zhang *et al.* 2018), and the rainfall reduction rates of permeable pavements range from 10.21% to 32.26% under the conditions of rainfall return period of 1–10 a (years) (Xu *et al.* 2020a, 2020b, 2020c). It has also been found (Al-Hasan *et al.* 2020) that asphalt materials with polymers and recycled aggregates are highly effective in improving the quality and performance of asphalt pavements, providing an experimental basis for studying the performance and pollutant reduction capacity of different materials for permeable pavements. For the study on the effect of urban stormwater runoff heat pollution control, some scholars believed that its heat pollution mainly comes from the heat exchange process during rainfall on urban impervious substrates, and the heat pollution load was influenced by multidimensional factors such as substrate type, impervious area ratio, rainfall characteristics and climatic conditions, and the land use type and development intensity should be reasonably controlled during urbanization (Ferrari *et al.* 2020); some scholars also believed that stormwater runoff reduced through low impact development techniques (green roofs, rain gardens, depressed green spaces and permeable pavements) infiltrated into the lower structural layers, and since the lower structural layers not directly affected by solar radiation are usually cooler than the surface layers, the average temperature of the water discharge decreased by 4.4–13.2 °C (Mohajerani *et al.* 2017; Li *et al.* 2020). However, since there were many types of permeable pavements and different pavement forms had various effects on the treatment of different pollutants and heat, it is important to screen out permeable roads suitable for different regions and functional areas for the application of low impact development techniques to treat urban stormwater runoff and alleviate water pollution.

Although the removal effects of permeable bricks and permeable concrete with N, P, SS, heavy metals, organic matter and other physical pollutants have been reported by scholars, less research has been conducted on the removal, evaluation and control effects of various permeable pavements with runoff pollutants and heat for multi-occasion applications. In this study, permeable cement blocks (CP-B-Cement), steel slag permeable blocks (SP-B), ceramic permeable blocks (CP-B-Ceramic), permeable asphalt pavement (PAP) and impermeable pavement (IAP) were used as research objects to investigate purification and based on the results of the above study, the contribution ratio and key factors of cooling and purification are discussed, in order to provide a scientific basis and engineering parameters for the ecological pollution control technology of stormwater runoff in China and the design of urban roads according to local conditions.

2. MATERIALS AND METHODS

2.1. Experimental system

The experimental system consisted of a simulated artificial rainfall unit and a pavement unit (Figure 1), where the dimensions of the pavement were 300 mm (length) × 300 mm (width) × 50 mm (height), and the materials were all plexiglass and the experimental system was designed with a 50-mm-thick insulation layer outside. The permeable pavement structure layer was surface layer, base layer and bedding layer from top to bottom, and the surface layer was permeable pavement (ceramic permeable brick, steel slag permeable brick, concrete permeable brick and permeable asphalt pavement); permeable brick was mainly divided into burning-free permeable brick and sintered permeable brick (Han *et al.* 2021), and according to the permeable brick commonly used in permeable pavement at home and abroad, we selected a burning-free permeable brick (concrete permeable brick) and two sintered permeable brick (ceramic permeable brick and steel slag permeable brick), and compared with traditional permeable asphalt pavement, the specific characteristics of the four materials are

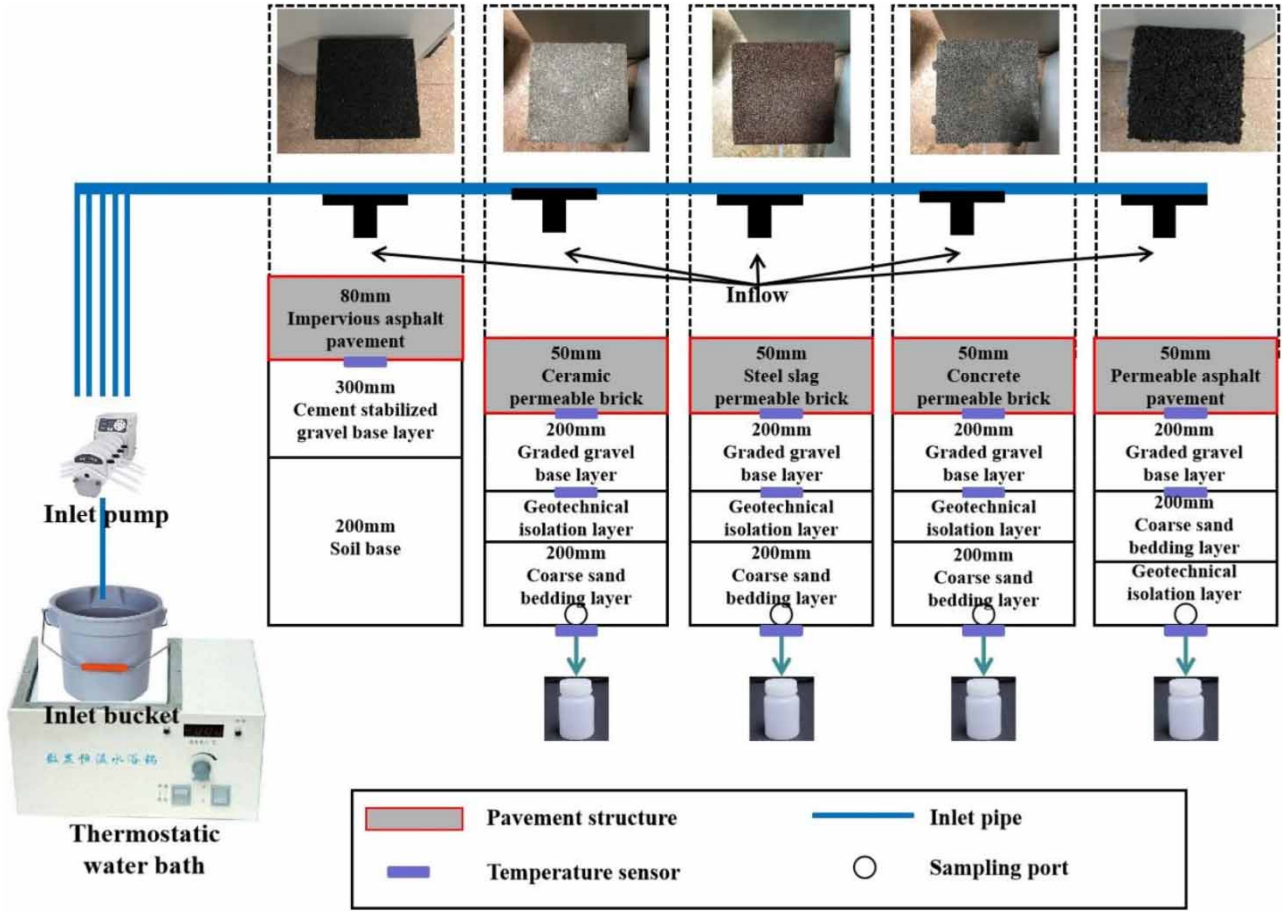

Figure 1 | Schematic diagram of the test system.

Table 1 | Properties of four permeable pavements

Items	Ceramic permeable pavement	Steel slag permeable pavement	Cement permeable pavement	Permeable asphalt pavement	GB/T25993-2010
Permeability coefficient (cm/s)	3.17×10^{-2}	2.62×10^{-2}	3.65×10^{-2}	2.31×10^{-2}	$\geq 2.0 \times 10^{-2}$
Void ratio (%)	24.97	24.21	26.72	21.83	≥ 15.0
Frost resistance (%)	4.0	2.7	4.7	/	Strength loss ratio $\leq 20\%$
Main chemical composition	Al_2O_3, SiO_2	FeO, Fe_2O_3	CaO, SiO_2	C, H, S, O	/

shown in Table 1; the base layer was graded gravel with 200 mm thickness, the bedding layer was coarse sand with 200 mm thickness, and the composition of the gradation of each layer was with reference to the *Specification for Construction and Acceptance of Water Permeable Brick Pavement* (DB11/T 686-2009) and *Technical Specification for Permeable Asphalt Pavement* (CJJ/T 190-2012) in China.

The impervious asphalt pavement structure was composed of surface layer, base layer and soil layer from top to bottom: the surface layer was made of impervious asphalt with a thickness of 50 mm; the base layer was cement-stabilized gravel with a thickness of 300 mm; and the soil layer was 100 mm thick. Temperature sensors were set at different locations in the experimental system: the impervious asphalt pavement had temperature sensor S1 at the outlet, and the permeable pavement had temperature sensors at the overflow outlet and the bottom of each structural layer to monitor the surface layer outlet temperature T1, base layer outlet temperature T2, bedding layer temperature T3 and water sample temperature T4, respectively. The water sample sampling port was set at the bottom of each device, and the samples were taken every 15 min in the first 1 h and every 30 min in the next 60 min according to the change of rainfall intensity.

2.2. Experimental design

According to the pollution characteristics of urban road stormwater runoff, dissolved nitrogen and phosphorus content dominate in road rainfall runoff (Wang *et al.* 2015; Wu *et al.* 2015). It was also found (Yuan *et al.* 2019) that total nitrogen and total phosphorus concentrations were significantly reduced in urban stormwater runoff after grassy swale treatment, and the removal of heavy metal ions reached 30.95%–97.39%. For this reason, the four pollutants TP, TN, Zn and Pb were selected as the object of this experiment. The rainwater used for the test was taken to be prepared manually, and the specific concentrations are shown in Table 2.

According to the monitoring characteristics of road surface layer in summer, three rainwater initial temperatures of 25, 32 and 40 °C and three groups of low, medium and high rainfall concentrations were selected, and the simulated artificial rainfall method was used. Different conditions (rain intensity and temperature) under different pavement structures on rainwater runoff cooling and purification characteristics were studied, respectively. The rainfall pattern was adopted from the generalized Chicago rainfall model (Luo *et al.* 2019), the rain peak coefficient was selected as 0.5 and the rainfall duration was all 2 h. The rainfall process curves at the recurrence periods $P = 0.5$, 1 and 3 a were simulated according to the storm intensity formula in Nanjing (Figure 2).

2.3. Analysis method

This paper used one-way ANOVA to compare the variability of runoff temperature and pollutant concentration for five groups of different road-types, and based on rainfall runoff and pollutant concentration data, the pollution load reduction rate (R_p) and the average temperature of secondary rainfall runoff (event mean temperature, EMT) were calculated for each permeable pavement, respectively, with the following equations:

$$R_c = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \tag{1}$$

$$\mathrm{EMT} = \frac{\sum Q_t \cdot T_t \cdot \delta_t}{\sum Q_t \cdot \delta_t} \tag{2}$$

$$\gamma_f = \left(1 - \frac{C \cdot \rho \cdot V_{out} \cdot \mathrm{EMT}_{out}}{C \cdot \rho \cdot V_{in} \cdot \mathrm{EMT}_{out}}\right) \times 100\% \tag{3}$$

Table 2 | Concentration of pollutants used in simulated rainfall test

Index	Actual rainwater concentration ($mg \cdot L^{-1}$)	Typical water distribution concentration ($mg \cdot L^{-1}$)	Chemical reagents	Simulation of low concentration ($mg \cdot L^{-1}$)	Simulation of high concentration ($mg \cdot L^{-1}$)	References
TP	0.26–3.73	1.2 ± 0.21	Potassium dihydrogen phosphate	0.71 ± 0.13	1.8 ± 0.47	Wang *et al.* (2015)
TN	1.32–21.66	6.0 ± 1.15	Ammonium chloride/ potassium nitrate	4.2 ± 0.27	7.0 ± 0.0.72	Luo *et al.* (2019)
Pb	0.042–0.75	0.3 ± 0.11	Lead chloride	0.2 ± 0.14	0.5 ± 0.41	Sountharajah *et al.* (2017)
Zn	0.057–1.33	0.5 ± 0.14	Zinc chloride	0.3 ± 0.20	0.72 ± 0.34	Rommel *et al.* (2021)
pH	6.17–8.42	7.0 ± 0.21	Sodium hydroxide/ hydrochloric acid	7.0 ± 0.21	7.0 ± 0.21	Yuan *et al.* (2019)

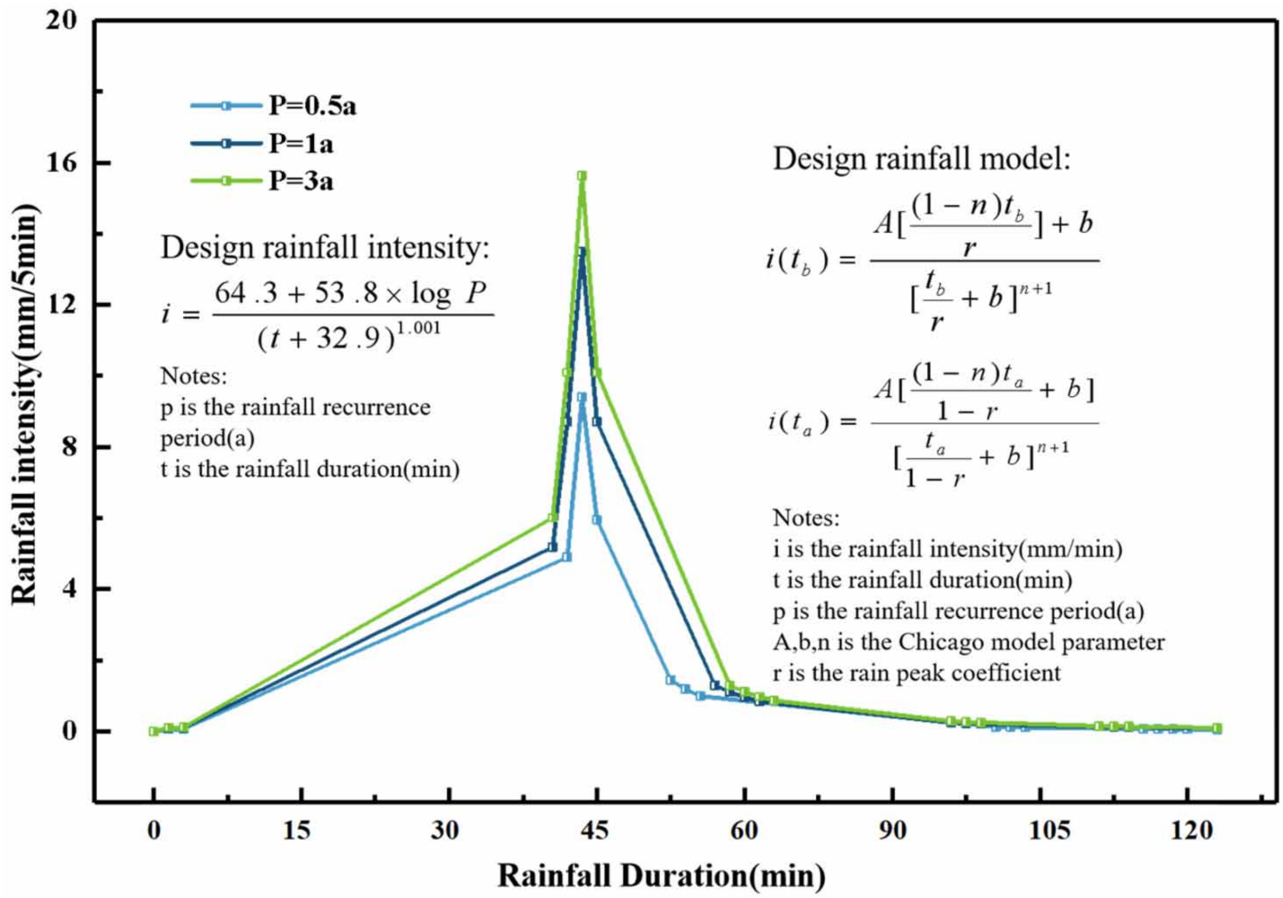

Figure 2 | Process of rainfall in different return periods.

where C_{in} is the stormwater pollutant concentration, $\text{mg} \cdot \text{L}^{-1}$; C_{out} is the effluent pollutant concentration, $\text{mg} \cdot \text{L}^{-1}$; R_{c} is the removal rate of each pollutant (TN, TP, Pb, Zn); γ_{f} is the field road runoff thermal pollution load reduction rate of permeable pavement, %; C is the specific heat capacity of water, 4.2 kJ/(kg °C); ρ is the density of water, 1×10^3 kg/m^3; V_{out} is the volume of rainfall runoff from the external discharge field, m^3; V_{in} is the volume of rainfall runoff from the field that sinks into the facility, m^3; Q_t is the field rainfall runoff flow rate, m^3/s; T_t is the field rainfall runoff temperature, °C; δ_t is the time increment, min; t represents time; and EMT_{out} is the average temperature of rainfall runoff from the external discharge field after the implementation of the rainfall runoff thermal pollution control facility, °C.

This paper was based on the fuzzy mathematical method for comprehensive evaluation of effluent water quality, according to the pollutant elements and the limits of surface water quality standards to determine the set of evaluation factors and evaluation criteria set according to the affiliation function formula (Equation (4)) to calculate the degree of affiliation. The fuzzy relationship matrix $R = (r_{ij})_{mn}$ was constructed and the weights were determined by using the superlative multiplier method of the non-equal weight method (Equation (5)). According to the principle of maximum affiliation, the water environment quality comprehensive judgment model ($D = W \times R$) was adopted to judge the category of water quality.

$$r_{ij} = \begin{cases} 1, & x_i \leq Q(j) \\ \dfrac{Q(j+1) - x_i}{Q(j+1) - Q(j)}, & Q(j) < x_i \leq Q(j+1) \\ 0, & x_i \leq Q(j+1) \end{cases} \tag{4}$$

where r_{ij} denotes the affiliation of the ith evaluation factor to the jth category of standards; x_i denotes the measured value of the ith pollution factor; and $Q(j)$ denotes the jth pollution factor of the first level of quality standard.

$$W_i = \frac{C_i/\overline{S_i}}{\sum_{i=1}^{n} C_i/\overline{S_i}} \tag{5}$$

where C_i denotes the measured value of the ith pollution factor; and $\overline{S_i}$ denotes the arithmetic mean of environmental quality standards at all levels for the ith pollution factor.

3. RESULTS AND ANALYSIS

3.1. Study on the pollutant blocking and controlling behavior of rainwater runoff

3.1.1. Purification effect of different types of permeable roads

In order to clarify the purification efficiency of different permeable roads for rainwater, the water quality change characteristics of permeable roads during the rainfall process were analyzed with the recurrence period $P = 1$ a and inlet water temperature of 32 °C as an example. The changes of pollutant concentrations in the effluent of different types of permeable roads during the course of the rainfall time are shown in Figure 3, where the pollutant effluent concentrations all gradually increased, with the lowest increase rate of TP and the highest increase rate of Pb. For the purification effect of TP, all permeable pavements show high removal efficiency, and the effluent concentration could be reduced to $0.4\ \mathrm{mg \cdot L^{-1}}$, which meets the limit value of TP for Class V water in the *Environmental Quality Standard for Surface Water* (GB3838-2002). Permeable asphalt pavement had the lowest removal rate of TP in runoff, and most of the effluent concentrations are higher than $0.3\ \mathrm{mg \cdot L^{-1}}$. Ceramic permeable pavement had the best removal effect of TP, and its removal rate could be increased by 76.7% compared with impermeable pavement, and the effluent quality was mostly lower than $0.2\ \mathrm{mg \cdot L^{-1}}$, which could meet the standard of Surface Class III water; meanwhile, the removal rates of TP of cement and steel slag permeable pavement were 79.4% and 81.3%, which were 71.6% and 72.9% higher than impervious pavement. The average concentration of TN in the effluent of all four types of permeable pavements was higher than $2\ \mathrm{mg \cdot L^{-1}}$, and the highest average concentration was found in the effluent of permeable asphalt pavement ($3.89\ \mathrm{mg \cdot L^{-1}}$), followed by ceramic permeable pavement ($3.25\ \mathrm{mg \cdot L^{-1}}$) and cement permeable pavement ($2.96\ \mathrm{mg \cdot L^{-1}}$), and the lowest concentration of TN in the effluent of steel slag permeable pavement ($2.59\ \mathrm{mg \cdot L^{-1}}$), and the removal rate could reach 57.5%, but none of them met the standard of Surface Class V water, indicating that the initial rainwater runoff infiltrated through the permeable pavement or directly discharged into the river and lake, which has a certain risk of pollution to the surface and groundwater.

The removal effect of permeable pavement types on heavy metal Pb varied widely, with cement permeable pavement outflow concentration of $0.15\ \mathrm{mg \cdot L^{-1}}$, which was higher than for the other permeable pavements, and ceramic permeable tiles had the best removal effect on Pb, up to 67.6%, but the average outflow concentration was still higher than $0.1\ \mathrm{mg \cdot L^{-1}}$, which could not reach the Surface Class V water standard. Compared with impervious pavement, the removal rates of Zn by cement permeable pavement, steel slag permeable pavement, ceramic permeable pavement, and permeable asphalt pavement increased by 52.8%, 55.7%, 62.3% and 70.2%, respectively, and the average concentration of Zn in the effluent of all four types of permeable pavement was lower than $0.3\ \mathrm{mg \cdot L^{-1}}$, which was much lower than the Surface Class V water standard ($2.0\ \mathrm{mg \cdot L^{-1}}$). This phenomenon may be caused by the high concentration of TP and Zn in the inlet water of the permeable asphalt pavement. During the simulated rainfall, the rainwater containing high concentrations of TP and Zn gradually filled the pores in the pavement structure and reached saturation, reducing the pollutant removal efficiency and resulting in the concentrations of TP and Zn in the effluent water quality exceeding the Class V threshold of surface water.

3.1.2. Evaluation of water quality of permeable pavement outflow based on the fuzzy mathematical method

The results of water quality evaluation are shown in Figure 4; with the extension of rainfall time, the overall water quality of different permeable pavement infiltration outflows became worse. In the early stage of rainfall, although most of the permeable pavement water quality was poor V, its fuzzy comprehensive index range was 4.93–5.43, slightly favoring V water. In the late stage of rainfall test, outflow water quality of four kinds of permeable pavement were poor V, permeable asphalt pavement was the worst and its fuzzy comprehensive index was 5.9; the different types of permeable pavement outflow water quality ranked as: SP-B > CP-B-Ceramic > CP-B-Cement > PAP, but compared with the initial infiltration runoff, the

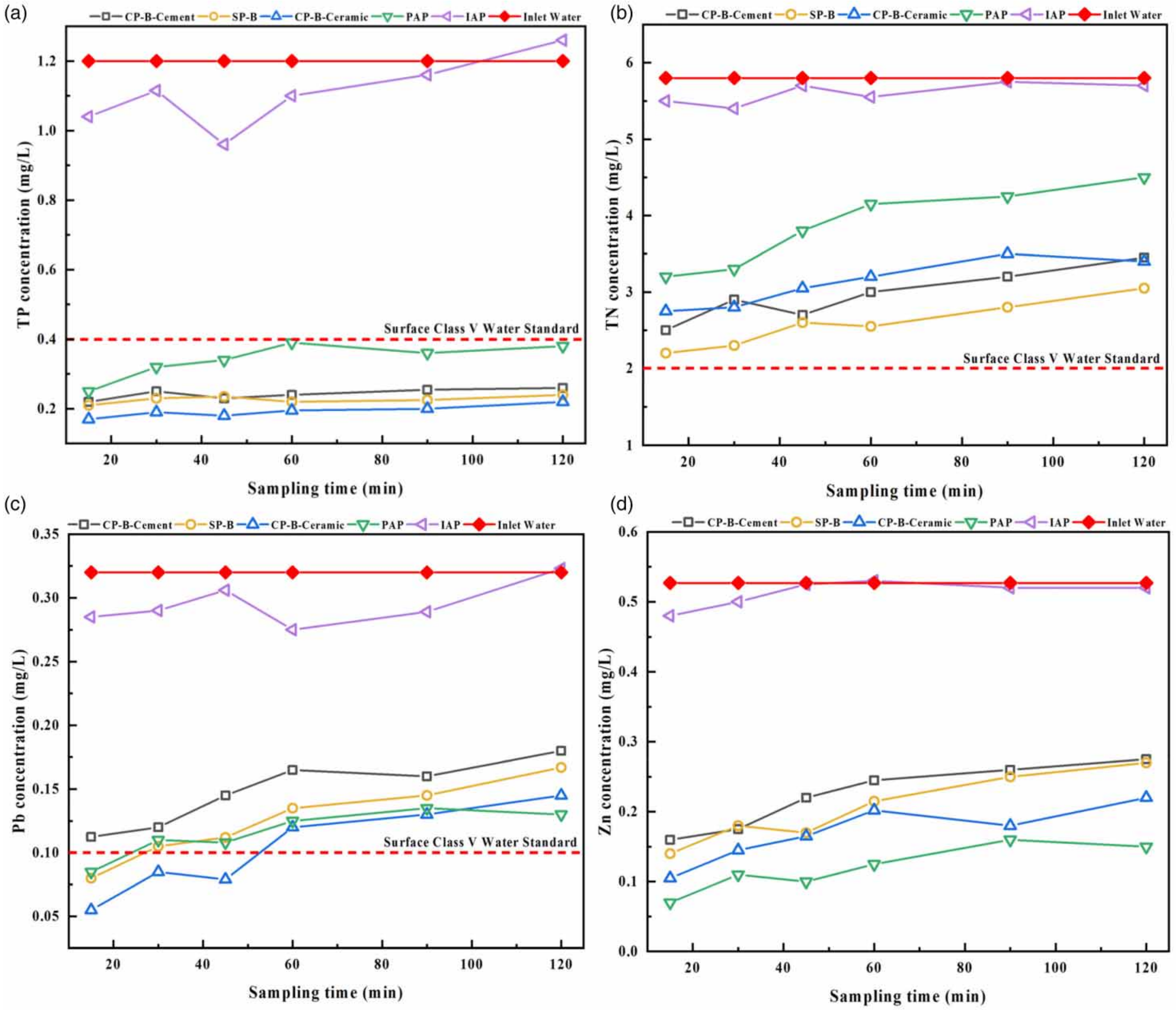

Figure 3 | Removal effect on different permeable pavements ($P = 1$ a).

permeable pavement surface had a certain control effect on pollutants such as nitrogen, phosphorus and heavy metals in the pavement runoff, but it was still difficult for the effluent water quality to reach the surface water standard. The weighting coefficients of Zn and TP were always small and had little influence on the effluent water quality; the weights of TN and Pb were greater than 0.2 and had a greater influence on the overall water quality, which was mainly related to the permeable pavement structure material, pollutant removal mechanism and pathway. To achieve the purpose of surface discharge, a combination of other infrastructural enhancements to treat stormwater runoff will be required subsequently.

3.1.3. Effect of pavement runoff concentration on the purification effect of permeable pavements

The removal rates of pollutants by the four types of permeable pavements under different pavement runoff concentrations are shown in Figure 5. For TP, with the increase of pollution load, the removal rates of all permeable pavements except cement permeable brick pavement increased significantly, and the average removal rates of cement permeable pavement and steel slag permeable pavement were higher than 90% under high pollution load, while the outflow of TN showed the opposite trend, and the runoff concentration changed from low to high when the average removal rates of the four permeable pavements for the two pollutants decreased by 25.9%, 26.3%, 20.6% and 10.8%, respectively. At higher pollution concentrations, the removal rates of all four permeable pavements for TN were below 40%, and the permeable pavements had a weaker

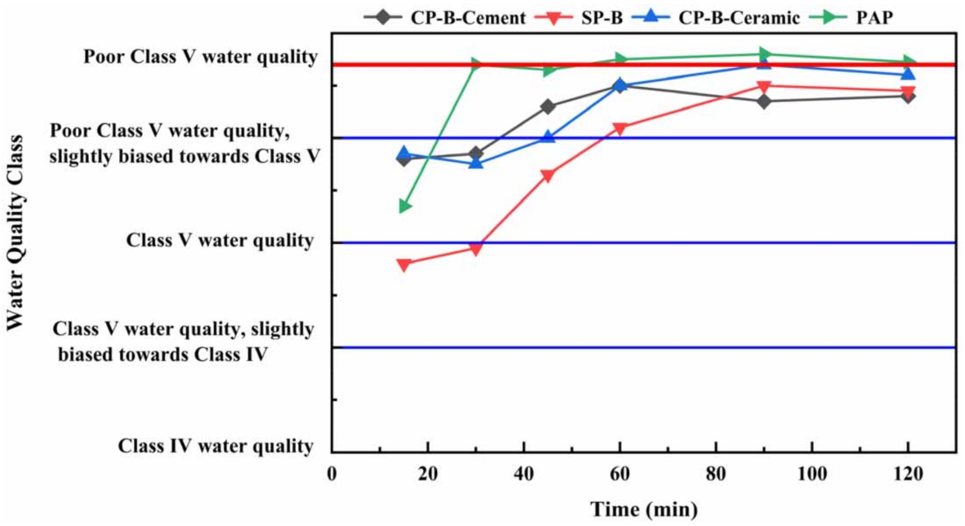

Figure 4 | Evaluation result of water quality in permeable pavement.

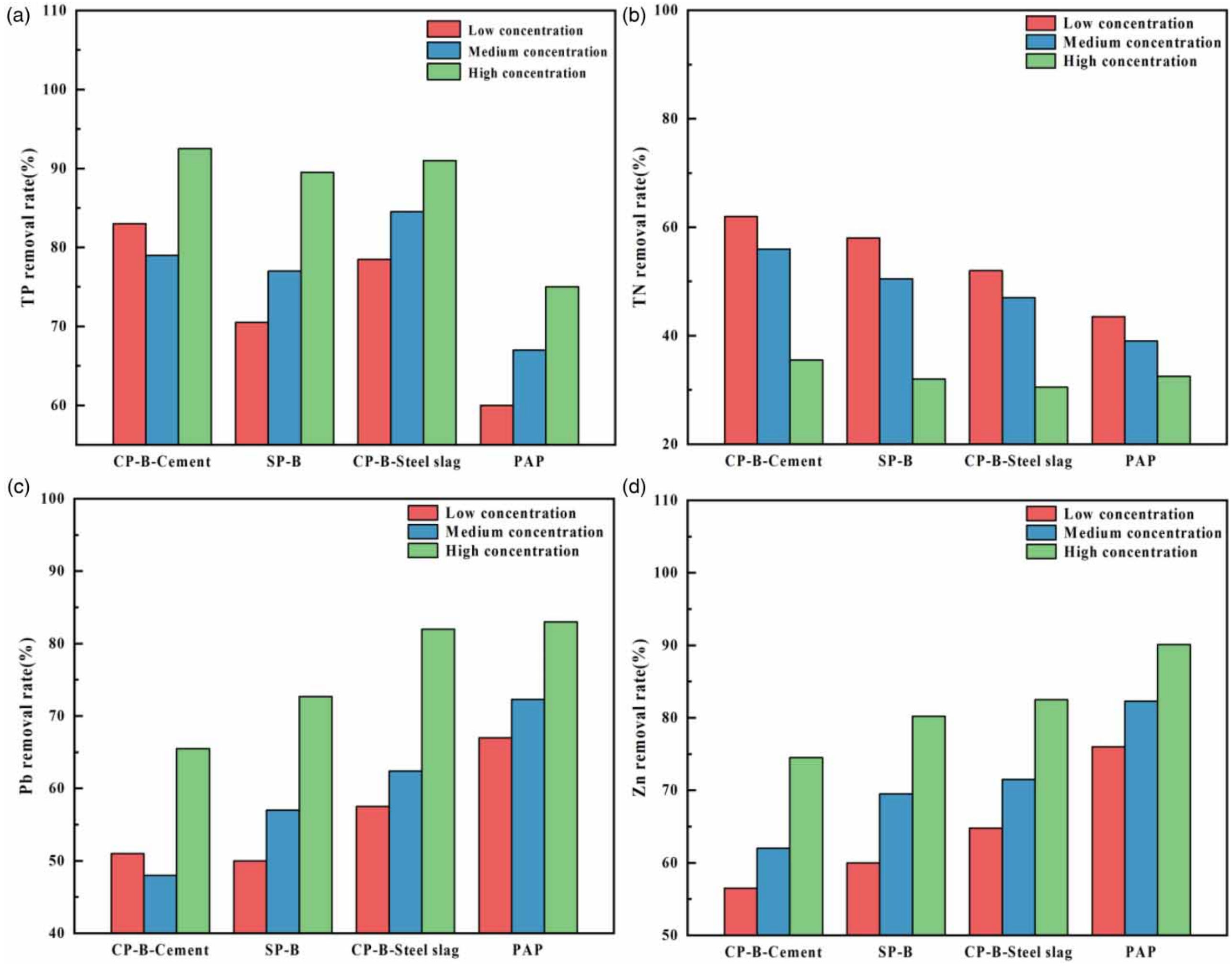

Figure 5 | Pollutant removal rates of four permeable pavements at different pollution loads ($P = 1$ a).

impact load resistance for TN. The main reason was that adsorption was the main way of nitrogen removal from permeable pavements, while the structural layers composed of asphalt, cement, steel slag, ceramic, gravel and coarse sand were designed with only strength, drainage or other road performance in mind, and the adsorption capacity of the selected materials was poor. In addition, nitrate nitrogen was generally removed by ion exchange, chemical reduction, or biological denitrification so that the amount reduced by adsorption was low (<10%), resulting in a low and unstable TN removal rate in stormwater runoff.

The influence pattern of road runoff concentration on the removal rate of Zn and Pb was similar to that of P. Moreover, the purification effect of permeable asphalt pavement was significantly higher than that of the other types of permeable pavement under different pollution loads, and the removal effect of Pb was improved to 65.7%, 78.2%, 81.7% and 84.1% for the four types of permeable pavement at high concentrations, which was 15%–25% higher compared with the purification effect for pollutants at low concentrations. The permeable cement pavement had the lowest removal rate (74.1%) for Zn, and the permeable asphalt pavement was 1.21, 1.13 and 1.09 times more effective than the cement, steel slag and ceramic permeable pavements, respectively, in purifying the infiltrated runoff for different concentrations of pollutants under high concentration pollution loads, and the permeable pavement types had different purification effects for different concentrations of pollutants.

3.1.4. Effect of rainfall intensity on the purification effect of permeable pavement

The changes in permeable pavement effluent water quality under three rainfall intensities are shown in Figure 6. With the increase in rainfall intensity, the effluent pollutant concentration gradually increased, and the pollution removal efficiency

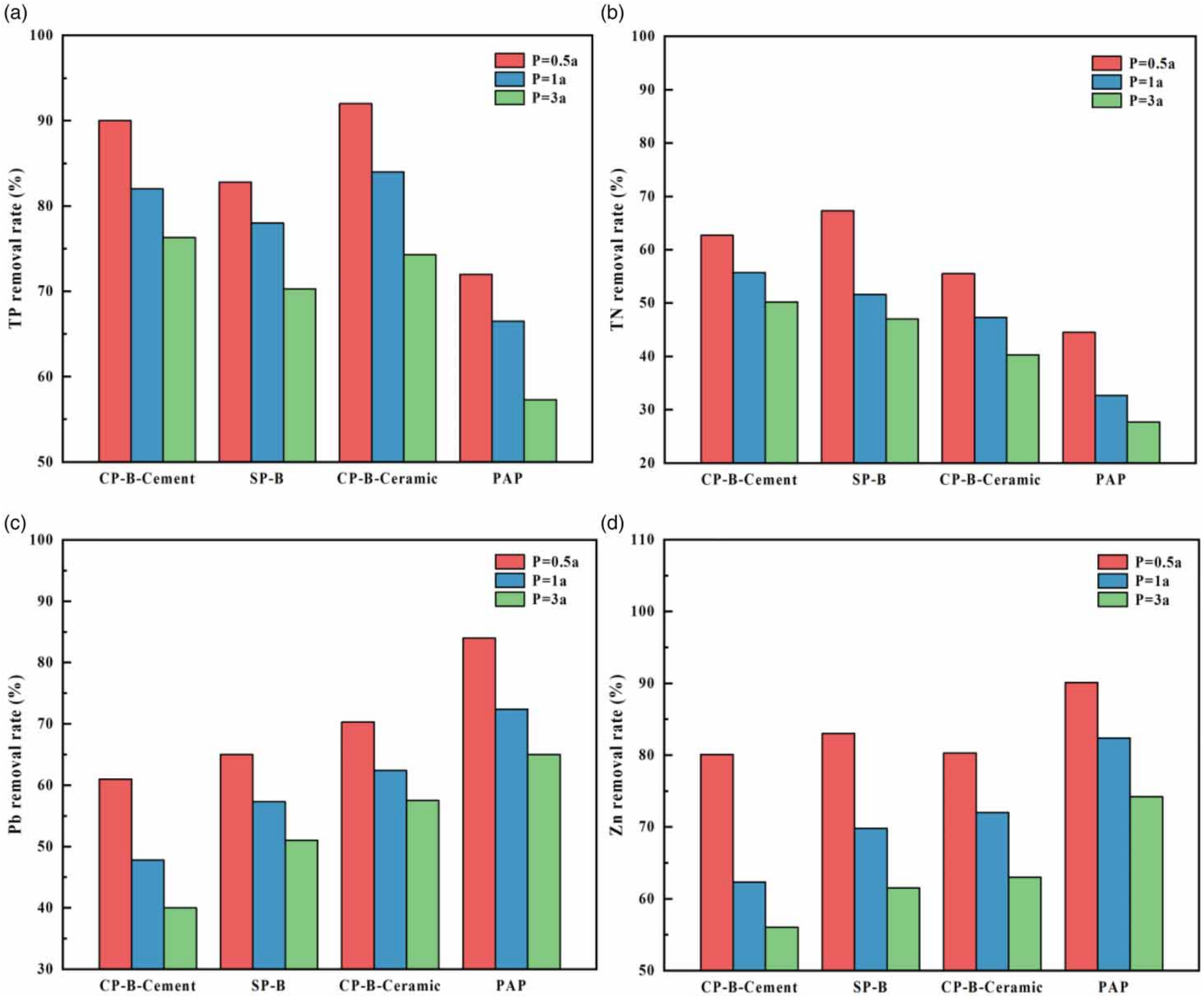

Figure 6 | Effluent concentration of pollutants of four permeable pavements under different rainfall intensities.

of all four types of permeable pavements showed a decreasing trend. For TP, when the rainfall return period increased from 0.5 to 1 a, the average removal rates of permeable asphalt, cement, steel slag and ceramic pavement decreased by 4.5%, 8.9%, 3.8% and 6.9%, respectively, and the pollutant removal rates of effluent stormwater under the 3 a recurrence period decreased by about 12.4%–17.1% compared with those under the 0.5 a rainfall recurrence period; the outflow pattern of TN affected by the rainfall return period was similar to that of TP; when the rainfall return period increased from 0.5 to 3 a, the removal rate of steel slag permeable pavement decreased the most, higher than 20%, and the cement permeable pavement had the least degree of influence, decreasing by 12.1%.

Rainfall intensity also had a greater influence on the removal rate of heavy metals Zn and Pb. When the rainfall recurrence period increased from 0.5 to 3 a, the removal rate of Pb decreased in the different types of permeable pavement by about 12.7%–21.1%; the decrease was the largest for permeable cement pavement, about 21.3%, the removal rate of Zn was the highest for permeable asphalt pavement and the least influenced by rainfall intensity, and the removal rate of permeable cement pavement was the most influenced by rainfall intensity, decreasing by about 24.3% when the rainfall recurrence period increased from 0.5 to 3 a. The degree of influence on different pollutants by rainfall intensity was in the following order: Zn > Pb > TN > TP, and the degree of influence of different permeable pavements by rainfall intensity was CP-B-Cement > SP-B > PAP > CP-B-Ceramic.

3.2. Research on the cooling effect of rainwater runoff

3.2.1. Study on the cooling effect of different types of permeable roads

In order to understand the degradation ability of different types of roads for stormwater thermal pollution in the summer high-temperature season, the cooling rate was examined for the case of recurrence period $P = 1$ a and influent temperature 32 °C, and the results are shown in Figure 7. For the initial outflow, the temperature followed the order $T_{\text{SP-B}} < T_{\text{CP-B-Cement}} < T_{\text{CP-B-Ceramic}} < T_{\text{PAP}}$. After the rainfall started, heat exchange occurred between the rainwater runoff and the road structure layer, and the temperature of the outflow gradually increased, reaching 23.4, 22.2, 23.7 and 25.8 °C, and stabilized after 80–100 min for each road surface. The thermal pollution load reduction rate of the four types of permeable pavement was 19.9%–30.2%, which was a significant reduction effect, and the effect of the four types of permeable pavement on thermal load reduction was: SP-B > CP-B-Cement > CP-B-Ceramic > PAP. The thermal pollution load reduction rate of steel slag permeable road was 2.72%, 2.89% and 10.29% higher than that of cement, ceramic and permeable asphalt pavement, respectively, and its thermal load reduction effectiveness was higher than that of the other types of pavements, and the four types of permeable pavement in this paper have significant thermal pollution control effects on stormwater runoff.

3.2.2. Influence of rainwater runoff temperature on the cooling characteristics of permeable pavement

To investigate the effect of different road runoff temperatures on the reduction of thermal pollution of permeable pavement, the cooling characteristics of the pavement were investigated for the cases of inlet temperature of 25, 32 and 40 °C, and the

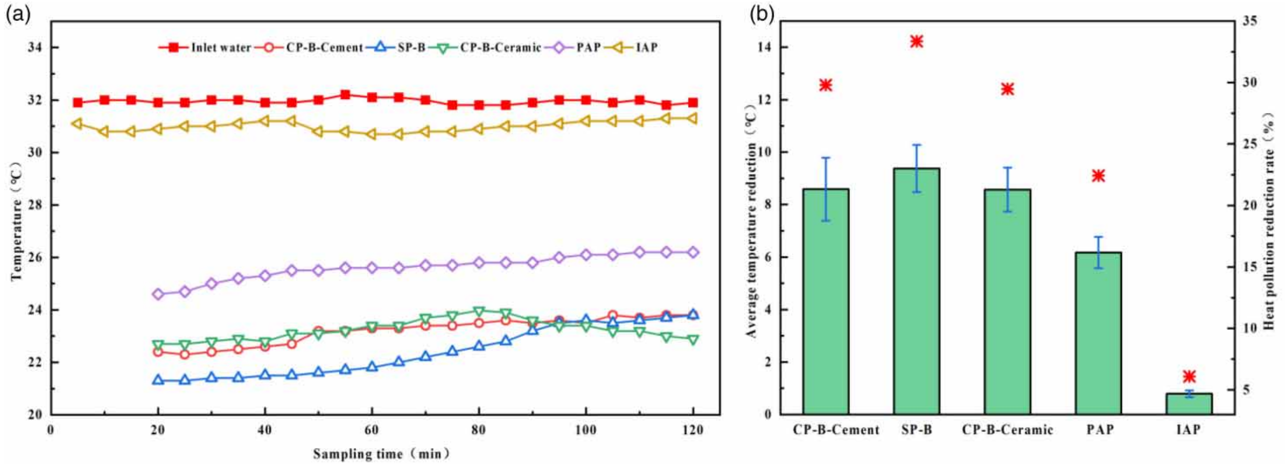

Figure 7 | Cooling characteristics of permeable pavements ($P = 1$ a, $T = 32$ °C).

results are shown in Figure 8. Regardless of the initial temperature change, the outflow temperature of permeable asphalt pavement was the highest (21.6, 25.5 and 30.3 °C), and the influence of inlet water temperature on permeable cement pavement was the least. When the inlet water temperature increased from 25 to 32 °C, the outflow temperature of permeable cement pavement increased the least, only 2.71 °C, and the outflow of permeable asphalt pavement was the highest, 3.95 °C. When the runoff temperature increased from 32 to 40 °C, the increase of ceramic permeable pavement outflow temperature was 9.59 °C, which was higher than that of permeable cement pavement (6.9 °C), steel slag permeable pavement (8.31 °C) and permeable asphalt pavement (8.69 °C). The heat pollution reduction rate increased with the increase of runoff temperature, and the highest heat reduction efficiency of cement pervious pavement was up to 36.25% when the inlet water temperature was 40 °C, and the lowest heat reduction efficiency of cement pervious pavement was only 13.73% when the inlet water temperature was 25 °C, and the degree of influence of rainwater runoff temperature on the cooling of pervious pavement was in the following order: $T_{\mathrm{PAP}} > T_{\mathrm{SP\text{-}B}} > T_{\mathrm{CP\text{-}B\text{-}Ceramic}} > T_{\mathrm{CP\text{-}B\text{-}Cement}}$.

3.2.3. Influence of rainfall return period on the cooling characteristics of permeable pavement

For the same infiltration runoff temperature, the change curves of different permeable pavement outlet temperatures showed similar trends under different rainfall return periods (Figure 9). When the rainfall return period was 0.5 a, the average temperatures of permeable asphalt, cement, steel slag and ceramic pavement outflow were 24.9, 21.6, 21.8 and 22.5 °C, respectively, and the reduction rate of thermal pollution was 22.1%–32.5%. When the rainfall return period increased to 1 a, the temperature of permeable pavement outflow gradually increased between 22.1 and 25.5 °C. The reduction rates of thermal pollution for permeable asphalt, cement, steel slag and ceramic pavement were 20.3%, 30.9%, 30.2% and 27.8%, respectively, and the cooling performance of each permeable pavement gradually decreased when the rainfall recurrence period increased to 3 a, compared with the return period of 0.5 a; the outflow temperatures of permeable asphalt, cement, steel slag and ceramic pavement increased by 2.4, 1.5, 0.7 and 1.8 °C, respectively, and the reduction rates of thermal pollution decreased by 4.7%, respectively. By comparing the above three different rainfall recurrence periods, the temperature reduction characteristics of the four types of permeable pavements gradually increased with the increase of the rainfall return period, and the thermal pollution load reduction capacity gradually decreased and stabilized.

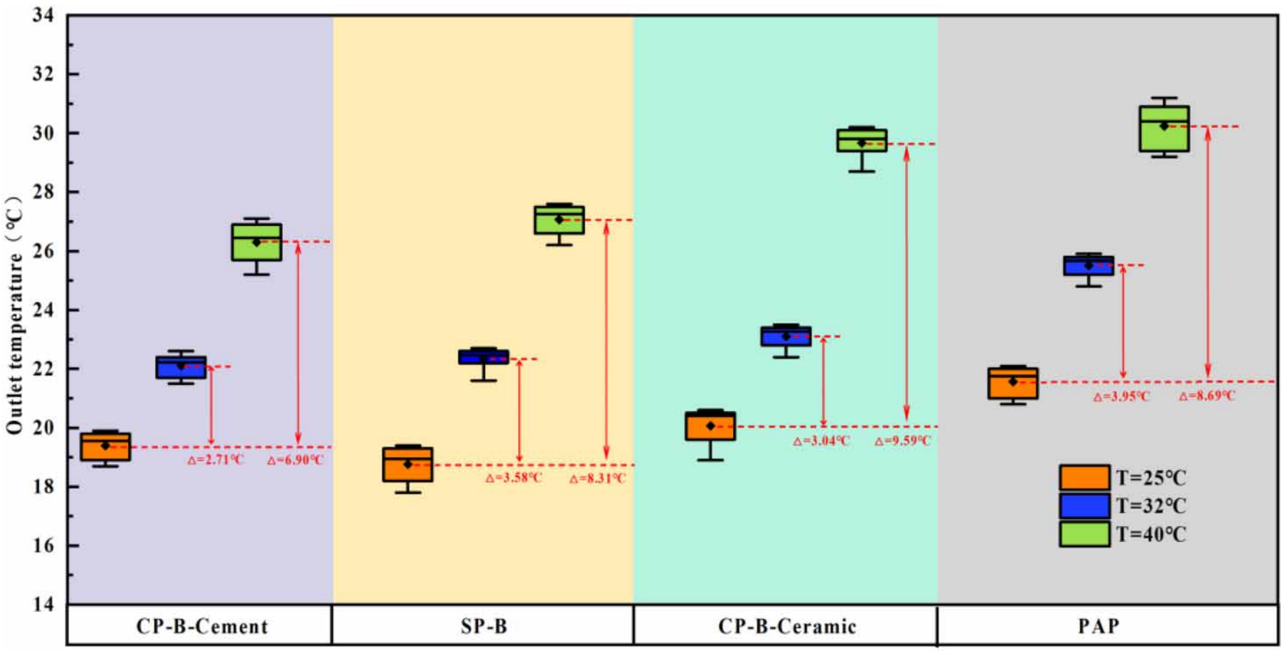

Figure 8 | Temperature change of effluent at different initial temperatures of permeable pavement ($P = 1$ a).

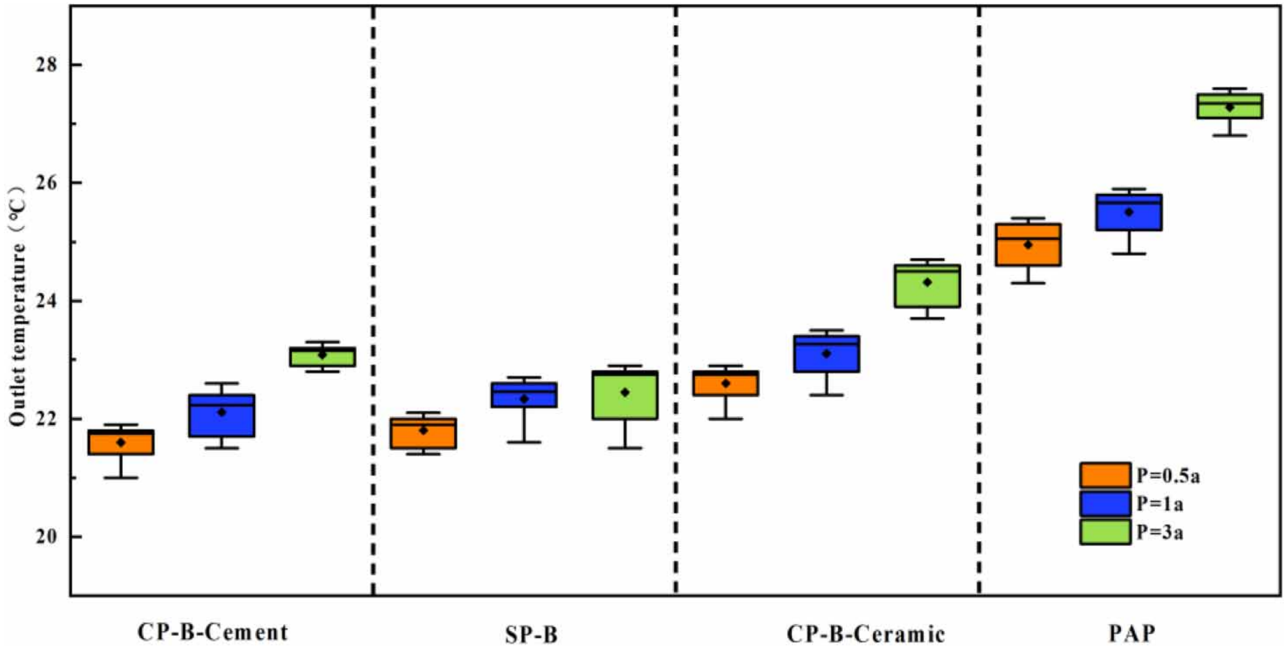

Figure 9 | Outlet temperature of permeable pavement under different rainfall intensities (inlet temperature = 32 °C).

4. DISCUSSION

4.1. Purification mechanism of stormwater runoff pollutants

Permeable pavements can effectively reduce harmful pollutant loads in road stormwater runoff while controlling runoff, but their purification effects are influenced by many random factors, such as road runoff water quality, rainfall characteristics and seasonal climate. In this study, the four types of permeable pavements showed advantages in all aspects of road runoff control over impervious pavements (Figures 3 and 6), which was similar to the results of Hernández *et al.* (2019). Ceramic permeable pavements showed the highest average pollution load reduction (65.3%), which was higher than that of steel slag permeable pavements (61.7%), cement permeable pavements (59.4%), permeable asphalt pavements (47.9%) and impermeable pavements (7.4%) in that order.

The main components of ceramic permeable pavement were Al_2O_3, CaO, MgO and Fe_2O_3, which very easily formed precipitation with soluble P in rainwater, and ceramic permeable tiles were fired at high temperature, and the surface of the road material had a large specific surface area and complex micro- and mesopore structure, which resulted in more effective adsorption sites, and therefore, its purification effect was optimal. In contrast, the highly viscous asphalt in the permeable asphalt infiltration channel was a mixture of a variety of complex hydrocarbons and derivatives of O, S and N. Some polar components such as carboxylic acid phenols and other oxygenated compounds could form more stable chelates with Pb^{2+} and Zn^{2+} in stormwater runoff (Zhang *et al.* 2020) (mechanism of action as in Equations (6) and (7)), prompting a better effect on heavy metal removal. Steel slag permeable pavement contained a large amount of FeO (22.94%), which could rapidly reduce nitrate, and zero-valent iron was converted into Fe^{2+}, Fe^{3+} and Fe_3O_4 after supplying electrons in the reduction reaction, and NO_3^-–N was reduced to N_2 and NH_4^+–N after gaining electrons (Guan *et al.* 2015), which largely improved the TN removal efficiency compared with the other pavements.

$$2R - COO^- + Pb^{2+} \rightarrow Pb(RCOO)_2 \downarrow \tag{6}$$

$$2R - COO^- + Zn^{2+} \rightarrow Zn(RCOO)_2 \downarrow \tag{7}$$

In general, the generated surface load of N, P and organic matter became higher with the increase of rainfall intensity, and the removal rate of TN by permeable asphalt pavement was even lower than 20% under the condition that the rainfall return period reaches 3 a. The study of Wang *et al.* (2019) found that the increase in rainfall intensity increased the infiltration rate of rainwater in permeable pavement, and reduced the hydraulic retention time between runoff and permeable materials, and reversible adsorption sites were occupied rapidly with the rise of infiltration, which led to a gradual increase in the concentration of various pollutants in the effluent. The results of this study showed that compared with other pollutants, the removal effect of TP and Zn showed a relatively stable trend under different rainfall intensities, and surface adsorption was the main removal pathway for phosphate and Zn, which was also revealed by similar studies; the impact load resistance of ceramic permeable pavement was relatively stronger than that of the other pavements, mainly due to the fact that ceramic permeable tiles were fired at high temperatures, and the surface of the pavement had a large specific surface area as well as a complex micro- and mesoporous structure, resulting in more effective adsorption sites. Although the average removal rate of pollutants in stormwater runoff from permeable pavement in this study ranged from 36.3% to 84.5%, the content of some pollutants (TN and Pb) still exceeded the limits of the surface water environmental quality standard (GB3838-2002). Obviously, it is difficult to achieve effective removal of different pollutants by infiltration of rainwater through permeable pavement alone, and other technical measures must be combined.

Some researchers have found that stormwater runoff with higher pollution concentrations leads to higher concentrations in permeable pavement outflow (You *et al.* 2019), and similar studies have shown (Jiang *et al.* 2015) that pollutant concentrations have a greater effect on pollutants with low removal rates and a smaller effect on pollutants with high removal rates. In this study, the removal efficiency of TP, Pb and Zn was increased for all four permeable pavements under extreme rainfall conditions at high concentrations, and only the effluent concentration of TN was gradually increasing, mainly because adsorption was the main way of nitrogen removal from permeable pavements, and the structural layers composed of asphalt, cement, steel slag, ceramic, gravel and coarse sand were designed only considering strength, drainage or other road performance, and the selection of the adsorption capacity of the materials was poor, and the limited adsorption sites made each construction material approach or reach the adsorption saturation amount in a short period of time. A large number of studies have shown (D. S. Li *et al.* 2019; J. Li *et al.* 2019) that root nitrate nitrogen was generally removed by ion exchange, chemical reduction or biological denitrification, and the amount reduced by adsorption is low ($<10\%$), resulting in a low and unstable removal rate of TN from stormwater runoff. Under extreme rainfall events with high concentrations, although road material voids may retain certain pollutants by trapping or adsorption, they were still retained inside the permeable pavement and may accumulate and be released leading to secondary pollution of the environment if not properly maintained at a later stage.

4.2. Cooling characteristics of permeable pavements

Previous studies found that LID facilities had the potential to mitigate thermal pollution from stormwater runoff (Sounthararajah *et al.* 2017; Rommel *et al.* 2021). D. S. Li *et al.* (2019) and J. Li *et al.* (2019) also showed that the synergy of multiple sponge-city infrastructures was more efficient in reducing thermal pollution than a single technology, with the average removal rates of thermal pollution from stormwater runoff for permeable asphalt, cement, steel slag and ceramic pavements being 19.9%, 27.5%, 30.1% and 27.4%, mainly for volume reduction and heat exchange to reduce the temperature of stormwater runoff. However, other studies suggested that their own material properties, construction system and water storage capacity were usually the main reasons for heat reduction (Wang *et al.* 2019). In this study, the reduction rate of runoff heat pollution from steel slag permeable pavement could reach 30% in the early stage, which was 8.6 °C higher than the outlet temperature of impervious pavement under the same temperature runoff and was lower than that of the rain garden studied by Xu *et al.* (2020a, 2020b, 2020c), but higher than permeable brick and permeable asphalt pavement, etc. Steel slag permeable pavement could increase convective heat exchange and promote the removal of thermal pollution due to its rough surface and strong thermal conductivity, and the higher the initial infiltration runoff temperature, the higher the thermal pollution reduction rate. The reduction rate of thermal pollution on impervious pavement and other permeable pavements was 3.1%–27.1%, which was at a low level. At the beginning of rainfall, the internal structural layer of permeable pavement was in a non-saturated state, and the percolation process of the permeable surface layer was 'water absorption – saturation – percolation'. When the inflow rate was greater than the percolation rate, rainwater was mostly stored in the water storage area, and the 'storage – slow release' process of rainwater played a major role in the volume reduction of permeable pavement. In the 'slow release' process, the temperature of the structural layer material was lower than the runoff temperature, and the deeper the layer, the lower the temperature of the structural material, the 'stored' runoff inside the permeable pavement aquifer and steel slag, gravel, ceramic, cement and asphalt mix. Li *et al.* (2013) showed that when the thermal conductivity of the material increased from 0.6 to 2.6 W/m/K, the average temperature of the surface layer decreased by about 7.0 K. The strong thermal conductivity could make the heat accumulated in the road surface layer be rapidly introduced into the lower layer of the structure, and in this study, $K_{\text{SP-B}} > K_{\text{CP-B-Ceramic}} > K_{\text{CP-B-Cement}} > K_{\text{PAP}}$; the surface layer material properties enabled materials such as steel slag and ceramics to increase convective heat exchange and faster heat exchange with the contacted rainwater runoff. In addition, the infiltration rate of rainwater had an important effect on the reduction of runoff pollutants and heat; the higher the rainfall intensity, the smaller the heat removal from the permeable pavement, which was consistent with the studies of Xu *et al.* (2020c).

In this study, the purification and cooling performance of four commonly used permeable pavements was evaluated by simulating rainfall with different characteristics (intensity, pollution load and runoff temperature). However, detailed studies have not been conducted on the pathways of pollutant removal in permeable pavements through void configuration and material properties, pollutant accumulation in the pavement, and the risk of groundwater contamination; the adsorption between stormwater runoff and permeable pavements and their removal efficiency for heavy metals, nutrients, organic matter and thermal pollution are important for long-term (longer rainfall cycles and more rainfall) operation. Therefore, our future research will focus on long-period experimental studies and the contribution ratios of different mechanisms (biotransformation, adsorption and energy transfer) to the removal of each pollutant from stormwater runoff by permeable pavement systems of different configurations.

4.3. Insights into urban road runoff management control

Choosing a reasonable type of underlayment can reduce rainwater runoff pollution. Wang *et al.* (2019) monitored permeable pavement in an outdoor test site of Guangzhou construction and found that permeable pavement surface materials could effectively decrease environmental heat pollution load, of which ceramic permeable tiles effectively reduced about 10 °C, while permeable concrete could only reduce about 5 °C. Compared with impervious roads, permeable pavement rainwater runoff was through infiltration into the grass-roots level, and its temperature was lower than the surface ambient temperature as the grass-roots level was not directly affected by solar radiation; a reasonable choice of rainwater control and utilization technology could also reduce rainwater runoff heat pollution, and green roofs collected heat and could reduce 15%–51% of the total urban heat through continuous use, 21%–44% of the total runoff and 33%–82% of the pollution load, with significant deterrent effect. In the process of sponge city development and construction, priority should be given to the use of source decentralized rainwater control and utilization technologies to control rainwater runoff pollution, such as permeable roads, rain gardens, green roofs, grass-planting ditches and recessed green areas. On the one hand, such source processing technologies could effectively control initial runoff with higher temperature, as the runoff infiltrated to the structural layers with lower temperature and fully contacted with the materials of each structural layer for heat energy exchange to reduce road runoff thermal pollution; on the other hand, these source treatment measures continued to increase the removal effect on the initial runoff of different pollutants, directly reducing the pollution load of stormwater runoff. In the receiving water body areas that were sensitive to temperature changes, we can try to establish relevant specification standards and control systems for road runoff thermal pollution in the process of land development and planning design to maintain the ecological balance of water bodies.

5. CONCLUSIONS

(1) The purification efficiency of four permeable pavements was in the order of CP-B-Ceramic > SP-B > CP-B-Cement > PAP, the removal rate of TN for all permeable pavements was lower than 60%, and the effluent water quality concentration was higher than the surface V water threshold, indicating that the initial stormwater runoff was infiltrated through permeable pavements or discharged directly into rivers and lakes, which had a certain risk of pollution to surface and groundwater.

(2) When the return period increased from 0.5 to 3 a, the temperature of permeable asphalt, cement, steel slag and ceramic pavement outflow increased by 2.4, 1.5, 0.7 and 1.8 °C, respectively. The cooling characteristics and pollutant reduction capacity of permeable pavement both diminished with increasing rainfall intensity; the higher the rainfall intensity, the lower the pollutant reduction capacity.

(3) The runoff heat pollution reduction of four permeable pavements was in the order of SP-B > CP-B-Cement > CP-B-Ceramic > PAP. Heat pollution reduction rate increased with the rise of runoff temperature, and the highest heat reduction efficiency of cement permeable pavement was up to 36.25% when the inlet water temperature was 40 °C. The surface material characteristics of steel slag and ceramic enabled the convective exchange of heat and accelerated the contact

with rainwater runoff for heat exchange. In addition, the effect of stormwater infiltration rate on the reduction of runoff pollutants and heat needed to be further investigated.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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