Rainfall runoff features of permeable sidewalk pavement

Liyuan Qiu, Yu Zhang, Sheng Zhang, Jingwei Zhao, Tengfei Wang and Qiang Wang

ABSTRACT

In urban areas, the buildings and pavements make it hard for rainwater to infiltrate into the ground. The hardened underlaying sub-crust has increased the total rainfall runoff, pushing up the peak flood flow. Drawing on the construction concept of sponge city, this paper probes deep into the materials in each layer of permeable pavement for sidewalks. Specifically, a runoff model was constructed for sidewalk pavements under rainfall conditions through numerical simulation and model testing. Using the precipitation pattern of Qingdao, China, several combinations of materials were subject to rainfall simulations, revealing how each permeable pavement controls and affects the surface runoff. The results show that the permeability of surface course and sub-crust directly bear on the starting time, peak flow, total runoff and runoff time of sub-catchment runoff; and the latter has a greater impact than the former on sub-catchment runoff.

Key words | model simulation, pavement structure, permeable material, rainfall runoff, sponge city

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HIGHLIGHTS

- Structural design of urban rainwater harvesting systems.
- Impact of permeable surface material on urban surface runoff.
- Impact of sub-crust material and thickness on urban surface runoff.

INTRODUCTION

With the rapid development of urban construction, the traditional pavement is gradually replaced by impermeable pavement materials such as asphalt, cement and concrete (Moore *et al.* 2016; Zhang *et al.* 2018; Chen *et al.* 2019; Coseo & Larsen 2019). While blocking the water transfer channel between rainfall and soil, these materials have also caused surges in the surface runoff in the cities, as floods and waterlogging occur frequently in the cities, the urban ecological environment has been seriously affected (Radfar & Rockaway 2016; Coble *et al.* 2018; Li *et al.* 2018; Qin *et al.* 2019).

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In 1933, Horton proposed the theory of rainwater runoff generation under the rainfall conditions. In order to reduce the flow of generated runoff, some scholars analyzed different low-impact development (LID) practices based on field experiments and found that LID practices have a greater impact on the ability to reduce surface runoff (Shafique & Kim 2017; Sobotkova *et al.* 2018; Shakya *et al.* 2019). Permeable pavement is an effective LID practice that plays an important role in reducing rainfall runoff in urban areas. Fassman *et al.* (Fassman & Blackbourn 2010; Wang *et al.* 2018) believe that permeable pavement can be taken as an LID-source control measure which can reduce the rainstorm runoff of traditional large-scale design; Kuruppu *et al.* (Kuruppu *et al.* 2019; Li *et al.* 2019) explored the influence of permeable pavement types, porous concrete/asphalt mixture design, aggregate material, particle size distribution, base depth and other design factors on the pavement's hydraulic performance, structural performance and environmental performance; Modi *et al.* (2018) established a concrete model and concluded that the permeable concrete pavement can absorb surface runoff through tests and analysis; Shafique *et al.* (2018) modified the permeable interlocking concrete pavement (PICP) and found that the PICP system is very effective in controlling rainfall runoff; Xie *et al.* (2017) found that the LID combination system (permeable pavement + grass swamp) is more effective than the sum of individuals in reducing total runoff and total peak flow; Drake *et al.* (2014) studied the influence of different types of permeable pavement structures on rainfall runoff reduction and water quality improvement.

Many scholars have done a lot of research on the theory of water-permeable pavement. However, the research focus on paving pavement mostly focuses on materials, and there is less research on structural design. In the construction of sponge cities, although the permeable concept has been introduced to some pavement, permeable pavement has been adopted, but most of them still stay in the level of changing the surface layer into major permeable materials, and the general effect is not satisfactory. Therefore, this study takes the composition materials of each layer of pavement structure as the research objects, aiming at the design of the ground structure of the permeable sidewalk pavement, numerical simulation and model test are combined to construct a runoff model of the pavement structure under rainfall conditions, so as to simulate the rainfall under different scheme combinations, and thereby studying the surface runoff control process of the permeable pavement and its influencing relationship.

MATERIALS AND METHODS

Background

'Sponge city' refers to the urban development mode of realizing natural accumulation, natural penetration and natural purification by strengthening urban planning and construction management, giving full play to the functions of rainwater absorption, infiltration and slow release of buildings, roads, green spaces, water systems and other ecosystems, and effectively controlling rainwater runoff. The construction concept of sponge city refers to the scientific and rational graphic design and vertical design of different LID practices and their combinations, and the comprehensive measures of 'infiltration, stagnation, storage, net, use and discharge' are taken to minimize the impact of urban development and construction on the ecological environment (Xu *et al.* 2018; Nguyen *et al.* 2019; Wang *et al.* 2020).

Based on the construction concept of sponge city, this paper takes the No. 9 line of Sino-German Eco-Park as the technical support to further optimize the road pavement structure and construct a physical scale model. The No. 9 line of Sino-German Eco-Park is located in the commercial residential area of the Sino-German Ecological Park in the Qingdao Economic and Technological Development Zone, Shandong Province, China. The No. 9 line starts from the No. 38 Line in the Eco-Park and ends at the No. 6 ring road of the park, and its specific geographic location is shown in Figure 1. The total length is about 241 m, the grade of the roads is urban branch road, and the red line width of the planned road is 18 m. The function of the road is mainly to meet the transport requirements of the residents on both sides of the road and to ensure the traffic demand inside the area.

Materials

This paper intends to take the permeable sidewalk pavement structure as a whole system to study it, rather than being

Figure 1 | Location of Sino-German Eco-Park.

limited to a certain kind of permeable material. In the research and analysis, this paper first selects and decides the materials for the pavement structure, materials of different parameters, and surface course; screed-coat, sub-crust and sub-base of different thicknesses are combined to form a permeable sidewalk pavement structure system to study the ability of the sidewalk pavement structure system to absorb rainwater under different scheme combinations. The specific parameters are as follows:

Material selection

(1) *Surface course of the permeable sidewalk*: this paper mainly selects the permeable pavement bricks widely used in the world as the surface course. There are two sizes of the permeable bricks: $100\ \text{mm} \times 200\ \text{mm} \times 40\ \text{mm}$ and $98\ \text{mm} \times 193\ \text{mm} \times 40\ \text{mm}$, their compressive strength ≥ 44.3 MPa, effective porosity $\geq 7.45\%$, and the saturated permeability coefficients are 8.5×10^{-4} and 3×10^{-4} m/s, respectively.

(2) *Screed-coat of the permeable sidewalk*: when the prefabricated sidewalk bricks are taken as the material for the surface course of the pavement, between the surface course and the sub-crust, a screed-coat with a certain thickness is required. According to China's *Engineering Technical Code for Rain Utilization in Building and Sub-District* (GB 50400-2016), this paper mainly selects medium-coarse sand as the material for the screed-coat, and the thickness of the sand layer is designed to be 20 mm.

(3) *Sub-crust of the permeable sidewalk*: for the material of the sub-crust of the permeable sidewalk pavement structure, according to the *Engineering Technical Code for Rain Utilization in Building and Sub-District* (GB 50400-2016), the thickness of the sub-crust of the permeable pavement is between 150 and 300 mm. In this paper, two kinds of materials are selected for the sub-crust: the graded broken stone and the cement-stabilized macadam, and the thickness of the sub-crust is designed to be 180, 200 and 300 mm.

(4) *Sub-base of the permeable sidewalk*: by collecting a large number of the geological survey data of Qingdao City and conducting engineering geological survey, it is known that most of the city's surface shallow areas are sandy soil or general clay with high sand content, rock ballast soil, and miscellaneous fill. The sandy soil base has excellent permeability and minimizes the load carrying capacity under saturated conditions. It is the best soil type for roadbed materials of permeable pavement structure, so this paper adopts sandy soil as the soil for the sub-base.

Determination of structure type and parameters

The design of the permeable pavement structure is mainly to meet the requirements of the permeable function, the load carrying capacity and the deformation of the pavement. This paper is based on China's *Engineering Technical Code for Rain Utilization in Building and Sub-District* (GB 50400-2016), when designing the structure, the chosen materials for each pavement structure mentioned above are taken as the research objects. For the structure of the permeable sidewalk pavement, different scheme combinations are proposed, the specific scheme combinations and the structure of the pavement are shown in Table 1 and Figure 2.

Rainfall data collection

This paper takes the Qingdao City which is located in the Shandong Province of China as the research background. The rainfall is calculated and sorted according to the *Specifications for Surface Meteorological Observation*, and, the formula for the storm intensity in Qingdao City is derived based on the method specified in the *Code for Design of*

Table 1 | Pavement structures of different combinations

Scheme	Composite structure type
1	Concrete permeable brick 40 mm + medium-coarse sand 20 mm + graded gravel 200 mm + sandy loam 2000 mm
2	Ceramic permeable brick 40 mm + medium-coarse sand 20 mm + graded gravel 200 mm + sandy loam 2000 mm
3	Ceramic permeable brick 40 mm + medium-coarse sand 20 mm + graded gravel 180 mm + sandy loam 2000 mm
4	Ceramic permeable brick 40 mm + medium-coarse sand 20 mm + graded gravel 300 mm + sandy loam 2000 mm
5	Ceramic permeable brick 40 mm + medium-coarse sand 20 mm + cement-stabilized gravel 200 mm + sandy loam 2000 mm

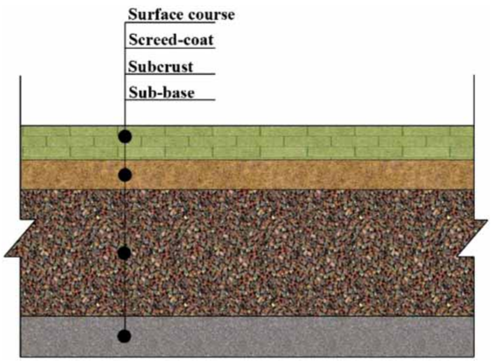

Figure 2 | Permeable sidewalk pavement structure.

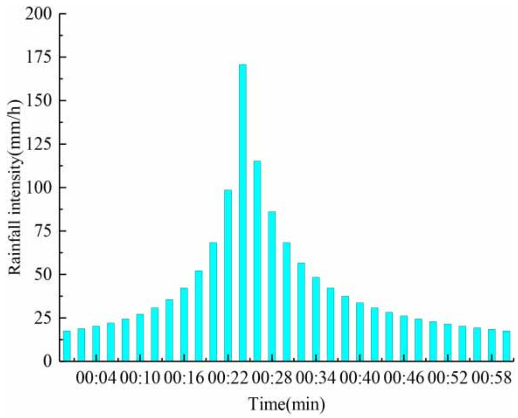

Figure 3 | Rainfall time-series diagram.

Outdoor Wastewater Engineering (GB 50014-2006) and screened according to the standards. It is recommended that Qingdao adopts the Chicago rain type.

According to the road design of the No. 9 line of Sino-German Eco-Park in Qingdao Economic and Technological Development Zone, the corresponding designed rainfall is a 60-min rain occurring once in 2 years, the calculation formula for the Chicago rain type is adopted to derive the rainfall data. The formula is as follows:

$$i = \frac{q}{167} = \frac{A \times (1 + c\lg P)}{167 \times (t + b)^n} \tag{1}$$

where P is the designed frequency (namely, the recurrence interval of the rainfall) and t is the designed rainfall duration.

According to the rainfall data of Qingdao, $A = 1909.009$, $b = 10.740$, $c = 0.997$, $n = 0.778$, which constitute the rainfall data under the designed rainfall intensity of Qingdao (China Meteorological Administration 2014). The designed rainfall is 44.18 mm, the rainfall duration is 60 min, and the rainfall intensity is 0.736 mm/min. The distribution of the rainfall and the change of peak intensity over time are shown in Figure 3.

Methods

Storm Water Management Model simulation

Based on the above five different permeable pavement structures, the Storm Water Management Model (SWMM) software was used to simulate the surface rainfall runoff generated by the sub-catchment of the pavement structure of different material combinations. Each permeable sidewalk pavement structure was generalized into a sub-catchment area, and the area of the sub-catchment was set to be 10.5 m^2 (3.5 m × 3 m), runoff gathering pits were set to collect the rainwater after road runoff was generated, and the rainwater would finally enter the water outlet. To facilitate the study, a simplified research model as shown in Figure 4 is established.

In the simplified model, the values of the model parameters are mainly based on geological engineering data and measured data values, regardless of material blockage. Based on the parameters of each pavement layer in the LID facility, the model is subject to simulation calculation, and the main parameter values are shown in Table 2.

The rainfall infiltration model adopts the Horton infiltration model, the surface runoff model is based on the nonlinear reservoir model, and the hydraulic model adopts the dynamic wave model. Since the permeable pavement is set to cover the sub-catchment area by 100%, no impermeable area has been set in the model, and the depression storage of the permeable area is set to 0. The model parameters of the slope of each sub-catchment area and the rainfall conditions of the rain gauge are consistent. The surface slope of the sub-catchment area of the runoff model is consistent with the slope of the sidewalk pavement structure, both set as 2%. The values of other model parameters are shown in Table 3.

Based on the above-mentioned model parameters and the designed 60 min rainfall intensity which would occur

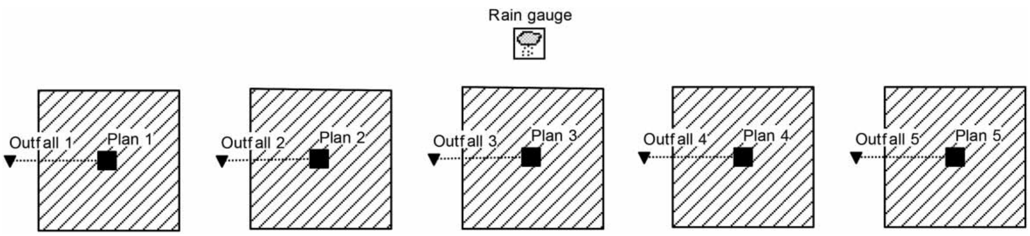

Figure 4 | SWMM construction.

Table 2 | Values of permeable pavement structural parameters under different schemes of model

	Project	**1**	**2**	**3**	**4**	**5**
Surface layer	Depression storage (mm)	2.54	2.54	2.54	2.54	2.54
	Vegetation coverage	–	–	–	–	–
	Surface roughness coefficients (n)	0.015	0.013	0.013	0.013	0.013
	Gradient (%)	2	2	2	2	2
Pavement layer	Thickness (mm)	40	40	40	40	40
	Porosity	0.31	0.35	0.35	0.35	0.35
	Impermeable surface ratio (%)	0	0	0	0	0
	Infiltration rate (mm/h)	1080	3060	3060	3060	3060
	Jam factors	0	0	0	0	0
Aquifer	Permeable base thickness (mm)	230	230	210	330	230
	Porosity	0.67	0.67	0.67	0.67	0.15
	Hydraulic conductivity (mm/h)	1044	1044	86.2	1044	1044
	Jam factors	0	0	0	0	0

Table 3 | Hydrological parameters of SWMM

The parameter name	**Physical meaning**	**Value range**	**The values**
N-Imperv	Manning coefficient of impermeable water area	0.01–0.03	0.015
N-Perv	Manning coefficient of permeable water area	0.1–0.3	0.235
Decay constant	Attenuation constant (h^{-1})	2–4	3.5
Drying time	Pre-drying time (d)	7–10	7

once in 2 years, the SWMM software was used to simulate five kinds of surface runoff situations in the sub-catchment area generated under the rainfall conditions.

Scale model test

According to the cross-section size of the No. 9 line in the Sino-German Eco-Park and the sponge city road design drawing (see Figure 5) with self-adjusting rainwater collection and utilization system designed according to the sponge city LID design concept, the arrangement between the two infiltration wells is selected as the test section with the size of 30 m × 18 m as a design unit. Considering the bearing capacity of the test platform and the feasibility of the road pavement, the design unit is scaled according to the ratio of 1:10, and the experiment on rainfall infiltration characteristics of permeable pavement structures under the designed rainfall recurrence interval conditions is carried out. The cross-sections of the scale model from north to south are 175 mm (sidewalk) + 200 mm (bicycle lane) + 250 mm (hedge) + 750 mm (motorway) + 250 mm (hedge) + 175 mm (sidewalk).

According to the design and distribution of the underlying pavement structure, the materials used for the sidewalks in the test are laid out according to the paving scheme proposed above. The materials for other pavement structural layers were arranged according to the design of the No. 9 line in the Sino-German Eco-Park, as shown in

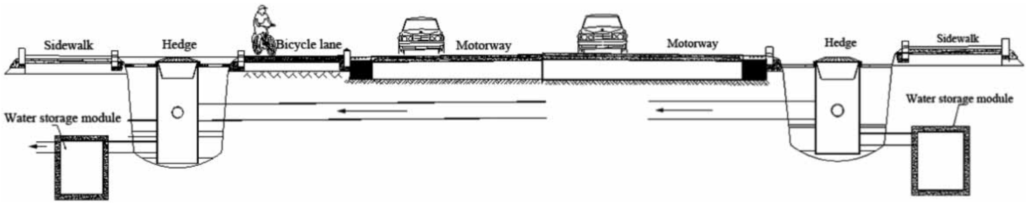

Figure 5 | Design of the No. 9 line in the Sino-German Eco-Park.

Table 4 | Structural layer material layout of functional pavement

Functional pavement	Structural layer material (top-down)	Gradient
Hedge	Artificial turf surface layer + plant the soil layer100 mm + soakaway geotextile 1–2 mm + sand layer 30 mm + soakaway geotextile 1–2 mm + gravel layer 40 mm + undisturbed sandy soil130 mm	/
Vehicular road	Weak permeability concrete 50 mm + cement-stabilized crushed stone base 60 mm + graded macadam cushion 60 mm + packed soil 80 mm	Two-way gradient 2%
Bicycle lane	Perlite exposed material permeable surface layer + permeable concrete base 50 mm + graded macadam cushion 60 mm + packed soil 240 mm	One-way slope 2%

Table 4. In the scale model established in this paper, for each functional area, except for the scheme combination of the sidewalk pavement having been changed, the parameters of other functional areas and the pavement schemes are the initial conditions of the test and remain unchanged.

To realize artificial rainfall in the experiment, a simulated rainfall spray system was installed in the upper part of the bearing platform in the test area determined according to the scale ratio; during artificial rainfall, the system realizes the equal substitution of artificial rainfall and rainfall under natural conditions by multiple artificial rainfall and adjusting the working power of the water supply pump. According to the designed rainfall intensity reached in the research area, it is required that the total duration of the rainfall is 60 min; the final scale model and the artificial rainfall device are shown in Figure 6.

RESULTS AND DISCUSSION

SWMM simulation analysis

Change law of runoff time

The simulation results of the runoff starting time, peak time, runoff ending time, and runoff time in the designed rainfall recurrence interval under each scheme combination are shown in Figure 7.

From Figure 7, we can see that:

(1) For the pavement structures of schemes 1, 2, 3, 4 and 5, the runoff starting time in the sub-catchment area was 00:16, 00:19, 00:19, 00:20, and 00:06, respectively; by comparing schemes 2, 3 and 4, we can know that, in the case of using the same permeable material for the sub-crusts, changing the thickness of the material has less influence on the starting time of the runoff in the sub-catchment area. By comparing schemes 1 and 5 with scheme 2, we can know that the runoff starting time of scheme 1 is 3 min earlier than that of scheme 2, and 13 min earlier than that of scheme 5. The results show that the runoff starting time in the sub-catchment area is directly related to the surface course of the pavement structure and the permeability of the material of the sub-crust. The influence of the permeability of the sub-crust material on the runoff starting time is greater than that of the surface course material.

(2) For schemes 1, 2, 3 and 4, the response times of the runoff peak of the sub-catchment area are all at 00:25, which is consistent with the rainfall intensity peak time adopted in the simulation, indicating that for the pavement structures using the same permeable material, under the conditions of the same rainfall recurrence

Figure 6 | Rainfall device and scale model.

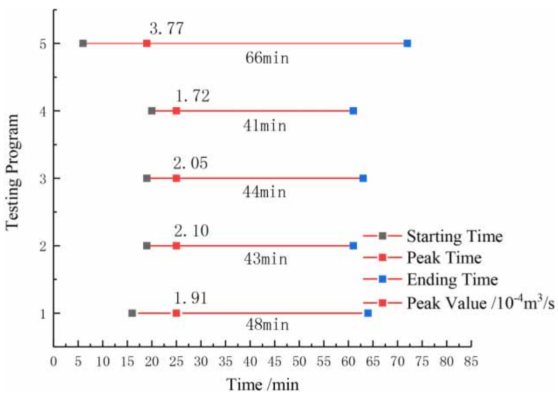

Figure 7 | Time map of regional runoff.

interval, the thickness of the underlying structural material has little effect on the runoff peak response time.

(3) Under the same rainfall conditions, the runoff durations of the sub-catchment areas in schemes 1, 2, 3, 4 and 5 are 48, 43, 44, 41 and 66 min, respectively; the runoff duration of the sub-catchment area in scheme 5 is the longest, which is 22 min longer than that in scheme 2; the runoff duration of the sub-catchment area in scheme 4 is the shortest, which is 2 min shorter than that in scheme 2. The above results indicate that, for the permeable sidewalk pavement structures, under certain rainfall conditions, improving the permeability of the underlying material can shorten the runoff time of the sub-catchment area. Increasing the thickness of the sub-crust material with better permeability can not only enhance the infiltration capacity and the retention space, but also largely reduce the runoff time of the sub-catchment area of the permeable sidewalk pavement structure.

(4) For schemes 1, 2, 3, 4 and 5, the peak flow of the runoff in the sub-catchment area is $1.91 \times 10^{-4}\,m^3/s$, $2.10 \times 10^{-4}\,m^3/s$, $2.05 \times 10^{-4}\,m^3/s$, $1.72 \times 10^{-4}\,m^3$ and $3.77 \times 10^{-4}\,m^3/s$, respectively; the peak flow of the runoff in the sub-catchment area of scheme 5 is the largest, which is 79.5% higher than that of scheme 2; the peak flow of the runoff in the sub-catchment area of scheme 4 is the smallest, which is 16.1% less than that of scheme 3, and 18.10% less than scheme 2. By

comprehensively analyzing the runoff starting time, runoff peak response time, and total runoff flow in the sub-catchment area of each scheme, it is found that sub-crust material with certain permeability can effectively reduce the peak flow of rainwater runoff, which can effectively delay the peak flow time of the runoff; however, changes in the permeability of the surface course material do not significantly reduce the peak flow of the rainwater runoff.

Variation characteristics of total runoff

For each scheme combination under the designed rainfall recurrence interval, the simulation results of the total runoff and runoff coefficient of the sub-catchment area of the pavement structures are shown in Table 5.

From the simulation results, under the same rainfall conditions, there are certain differences in the total runoff and runoff coefficients of different permeable pavement material scheme combinations, wherein the total runoff and corresponding runoff coefficients of scheme 4 are the smallest, which are 10.98 mm and 0.249, respectively, the total runoff reduced by 13.27% compared with scheme 2, and the runoff coefficient decreased by 12.94%; the total runoff and corresponding runoff coefficients of scheme 5 are the largest, which are 27.91 mm and 0.632, respectively. In summary, setting sub-crust material with good permeability can not only delay the peak flow time of the runoff, but also reduce the runoff flow of the rainwater and the runoff coefficient.

Scale model test results

During the test, the surface runoff of the sidewalks under each scheme combination was observed, the surface runoff of the sidewalk and the starting and ending times of the surface runoff flowing through the side drains of the sidewalk were recorded. The surface runoff and the drainage situation of the sidewalk are shown in Figure 8. The specific test results are shown in Figure 9 and Table 6.

It can be seen from Table 6 and Figure 9 that after raining for some time, surface runoff began to generate in each scheme combination, the surface runoff staring times of schemes 2, 3 and 4 are basically the same, the runoff

Table 5 | Study area runoff

Different combination scheme	Rainfall (mm)	The total runoff volume (mm)	The runoff coefficient
1	44.17	13.05	0.295
2	44.17	12.66	0.286
3	44.17	13.49	0.305
4	44.17	10.98	0.249
5	44.17	27.91	0.632

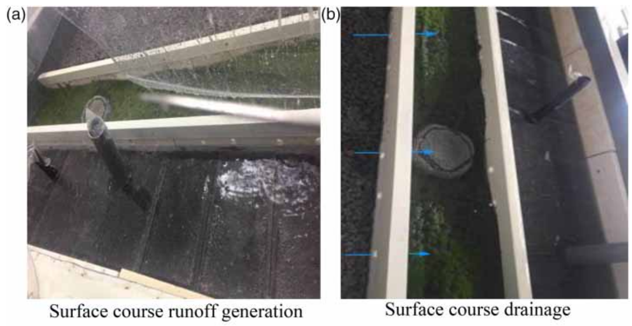

Figure 8 | Flow phenomenon of sidewalk pavement surface.

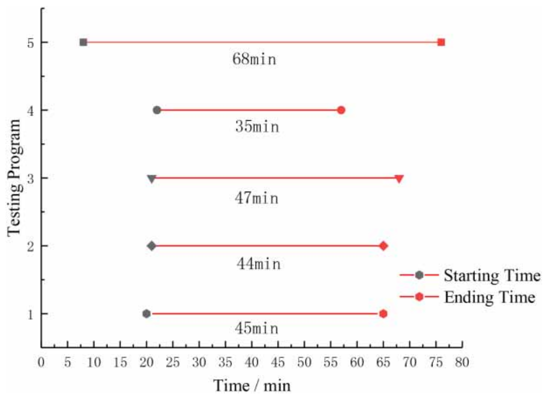

Figure 9 | Runoff moments on the pavement surface.

Table 6 | Relevant indicators of surface material runoff

Different combination scheme	Duration of rainfall (min)	Surface runoff time (min)	Surface drainage starts	End time of surface drainage
1	60	45	00:27	00:57
2	60	44	00:31	01:01
3	60	47	00:28	01:02
4	60	35	00:34	00:58
5	60	68	00:11	01:08

duration shortens with the increase of the thickness of the graded broken stone sub-crust, indicating that under the same rainfall and sub-crust material conditions, the change of the thickness of the sub-crust has little effect on the starting time of surface runoff, but we can shorten the surface runoff duration by enhancing the water storage capacity of the sub-crust.

By comparing the test results of schemes 1, 2 and 5, we can know that the surface runoff starting time of scheme 2 is 1 min behind that of scheme 1; the runoff duration is shortened by 1 min, which is 13 min behind that of scheme 5, and the runoff duration is shortened by 23 min. It can be seen that the permeability of the surface material has little effect on the runoff infiltration capacity of the overall pavement structure, and this result is consistent with the SWMM simulation result; the permeability of the sub-crust material can directly affect the infiltration speed of the surface rainwater, thereby affecting the starting time and duration of the surface runoff. Therefore, the better the permeability of the sub-crust material, the faster the water drainage, and thus the rainwater runoff time is reduced. Under different scheme combinations, after the surface runoff has generated for a period of time, the rainwater accumulated on the surface is discharged through the roadside drainage holes, and the corresponding drainage time parameters have similar rules.

CONCLUSIONS

Based on the construction concept of sponge city, this study took the composition materials of each layer of the sidewalk pavement structure as the research objects, aiming at the permeable sidewalk pavement structure types, it combined numerical simulation with the model test to construct a runoff model for sidewalk pavement structure under the rainfall conditions. With the precipitation pattern of Qingdao City in China as the research background, the rainfall simulation under different scheme combinations was carried out to study the surface runoff reduction and control process of the permeable pavement and its influencing relationship. The main conclusions are as follows:

(1) This study combines SWMM numerical simulation with the physical scale model test. By comparing schemes 1 and 2, we can know that in the SWMM simulation, the starting time of surface runoff in the sub-catchment area of scheme 2 is delayed by 3 min compared with scheme 1, in the physical scale model test, the starting time of surface runoff in the sub-catchment area of scheme 2 is delayed by 1 min compared with scheme 1; the runoff response times of sub-catchment area of both schemes are at 00:25; the runoff duration in the sub-catchment area of scheme 2 is shortened by 5 min compared with scheme 1; the peak flow of runoff in the sub-catchment area of scheme 2 is increased by 9.9% compared with that of scheme 1; the total runoff and the runoff coefficient of scheme 2 are reduced by 0.39 mm and 0.009, respectively, compared with scheme 1. Therefore, the increase in the permeability of the surface course material can improve the early water infiltration speed of the entire pavement structure, thereby effectively delaying the starting time of the runoff in the sub-catchment area, but its effect on reducing and controlling the peak flow of the rainwater runoff is not significant, and cannot truly change the 'retention and storage' performance of the entire permeable pavement structure.

(2) The comparison of schemes 2, 3 and 4 shows that: the runoff starting times in the sub-catchment area of schemes 2 and 3 are the same, the runoff starting time of scheme 4 is 1 min later compared with schemes 2 and 3; the runoff response times of the sub-catchment area of the three schemes are all at 00:25; the runoff duration of the sub-catchment area of scheme 4 is the shortest, which is 2 min shorter than that of scheme 3, and 3 min shorter than that of scheme 2; the runoff peak flow of the sub-catchment of scheme 4 is the smallest, which is 16.1% less than that of scheme 3, and 18.10% less than that of scheme 2; the total runoff and the corresponding runoff coefficient of scheme 4 are the smallest, the total runoff is reduced by 13.27% compared with scheme 2, and the runoff coefficient is reduced by 12.94%. It can be seen that increasing the thickness of the sub-crust material with better permeability can reduce the runoff flow and peak flow of the sub-catchment area and reduce the runoff time, but it cannot effectively delay the response time of the runoff peak.

(3) The comparison of schemes 2 and 5 shows that: in the SWMM simulation and the physical scale model test, the starting time of surface runoff in the sub-catchment area of scheme 2 is delayed by 13 min compared with scheme 5; the runoff response time in the sub-catchment area of scheme 2 is delayed by 6 min compared with scheme 5; the runoff duration of the sub-catchment area of scheme 2 is shortened by 22 min compared with scheme 5; the peak runoff flow of the sub-catchment area of scheme 2 increases by 9.9% compared with scheme 5; the total runoff and runoff coefficient of scheme 2 are reduced by 15.25 mm and 0.346, compared with scheme 5. The data show that the permeability of the sub-crust material can directly affect the surface rainwater infiltration speed, thereby affecting the surface runoff starting time and the runoff duration.
(4) The above research results show that the change of permeable surface course material has less effect on the reduction of urban surface runoff, while the sub-crust material with good permeability and the thickness of the material have significant influence on the urban surface runoff; the permeable pavement structure of scheme 5 is the optimal solution, and this scheme has certain reference value for the actual engineering projects.

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