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Experimental study on rainfall-runoff relation for porous pavements

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ABSTRACT

Impervious surfaces have long been implicated in the decline of watershed integrity in urban and urbanizing areas. Porous pavement is one solution to mitigating the problem of stormwater runoff problems. In this research, three available porous pavement systems were investigated to evaluate their infiltration capability of precipitation. Experiments were conducted to simulate different kinds of porous pavements having different sub-base materials in different cells. The discharge volumes were monitored from each cell, and the relationship between rainfall intensity, outflow and outflow duration was analyzed. Results show that these three porous pavements increased infiltration and decreased runoff. The optimum thickness of the porous pavement was 31 cm, which consisted of a 6 cm top layer of porous concrete and a 25 cm sub-base (10 cm concrete without sand and 15 cm aggregate base). Furthermore, under a rainfall rate of 59.36 mm/h, the runoff coefficient of the above porous pavement was zero, while the coefficient of the impervious pavement was 0.85. These results provide a clear indication of the value of porous pavement systems for broad expanses of the human engineered environment.

Key words | artificial rainfall, porous pavement, rainfall infiltration, runoff coefficient, sub-base

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INTRODUCTION

Impervious surfaces have long been implicated in the decline of watershed integrity in urban and urbanizing areas as cites are being covered by more buildings and airproof concrete road surfaces (Klein 1979; Pratt 1999, 2002). Rainwater cannot infiltrate into the subsurface because of the low permeability of the traditional concrete pavement. In addition, it is difficult for soil to exchange heat and moisture with air, and consequently the temperature and humidity of the Earth's surface in large cities cannot be adapted, causing the phenomenon of heat islands around cities. The creation of any large impervious surface commonly leads to multiple impacts on stream systems. These impacts include higher peak stream flows, which cause channel incision, bank erosion and increased sediment transport (Trimble 1997; Konrad *et al.* 2002; Nelson & Booth 2002). Another impact mentioned above, a reduction of infiltration, lessens groundwater recharge and potentially lowers stream base flows (Klein 1979).

Porous pavement is one solution for mitigating the problem of stormwater runoff problems (Field 1985; Pratt *et al.* 1989; Pratt 1995; Watanabe 1995; Wada *et al.* 1997; Benedetto 2002). Porous pavement systems commonly consist of a matrix of concrete blocks or a plastic web-type structure, with voids filled with sand, gravel or soil. These voids allow stormwater to infiltrate through the pavement into the soil.

The purpose of this paper was to examine the runoff control effects for the three types of infiltration facilities, with the assumption that, if they can infiltrate stormwater reliably, they then present an attractive replacement for the current structural requirements for stormwater management.

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METHODS

Experiment apparatus

This experiment was carried out in Mentougou experimental station of Beijing Hydraulic Research Institute, which specializes in runoff utilization.

Four experimental steel cells were used (Figure 1), with each cell measuring 2 m × 3 m. There were drainage boards under the cells, which had φ 1.0 cm holes. Water outlets were set up under the holes to monitor the quantity of the collection water. Pipes were used to collect both surface runoff and subgrade infiltration. Surface runoff and subgrade drainage from each cell were measured with beakers and flasks at the rear of each cell through drainage pipes for each of the three types of porous pavements and the impervious cell. Precipitation and runoff rates were recorded every 5 min.

An artificial rainfall apparatus was constructed on an adjustable shelf. It consisted of 36 Rainbird 1,800 sprinklers, with an operating pressure of 0.1 MPa, a discharge rate of 0.1 m^3/h and a insufflation area of 1.2 m × 4.0 m. The uniformity of the rainfall intensity is 0.905 and is controlled by sprayer combination.

Experiment treatments

Precast blocks were constructed with low-fine concrete, which results in many small, interlinked internal voids throughout the block sections. These precast blocks are laid on a recommended sub-base, which varied from a sub-base of relatively impermeable material to clean gravel and crushed rock, or other open-textured support. These remain free-draining provided they have regular maintenance, keeping the surface void spaces and joints between blocks free of debris. Typical uses are for public, light load surfaces of high frequency such as shopping center parking lots, footpaths along avenues, and pavements in courtyards.

Figure 1 | View of different porous pavement test cells.

The four cells were filled with three types of commercially available porous paving material which are generally available and used in Beijing, with an impervious surface as a control. The treatments are shown in Figure 2:

- Treatment A, porous concrete block paving with sub-base of 20 cm sand.
- Treatment B, porous concrete block paving with sub-base of 10 cm thick concrete lacking sand and 15 cm thick gravel.
- Treatment C, porous concrete block paving with sub-base of 5 cm thick concrete lacking sand and 20 cm thick gravel.
- Treatment D, impervious surface.

Experiment materials

The four cells were all filled with subgrade soil of light loam, packed to the bulk density and appointed position, with the physical parameters listed in Table 1. Low compressibility subgrade soil was sampled locally. The infiltration coefficient of the subgrade soil was 2.28×10^{-5} cm/s and the optimal volumetric moisture content was 0.236 $cm^3\,cm^{-3}$.

The soils were prepared by adding water or baking appropriately, weighing and mixing, in accordance with the Rules of Geotechnical Testing (SL237-1999). After tamping to the standard compaction degree of 0.9, the four cells were filled with the prepared soil. In order to maintain the designed density, five layers of subgrade soil were inspected using a core sampler during the course of filling. Inspection verified that the filling depth, vertical slope, transverse slope and sideline all satisfied the design requirements.

The sub-base consisted of macadam, sands and concrete lacking sands. The porous pavements formed separate reservoirs within the pavement, each filled with a different

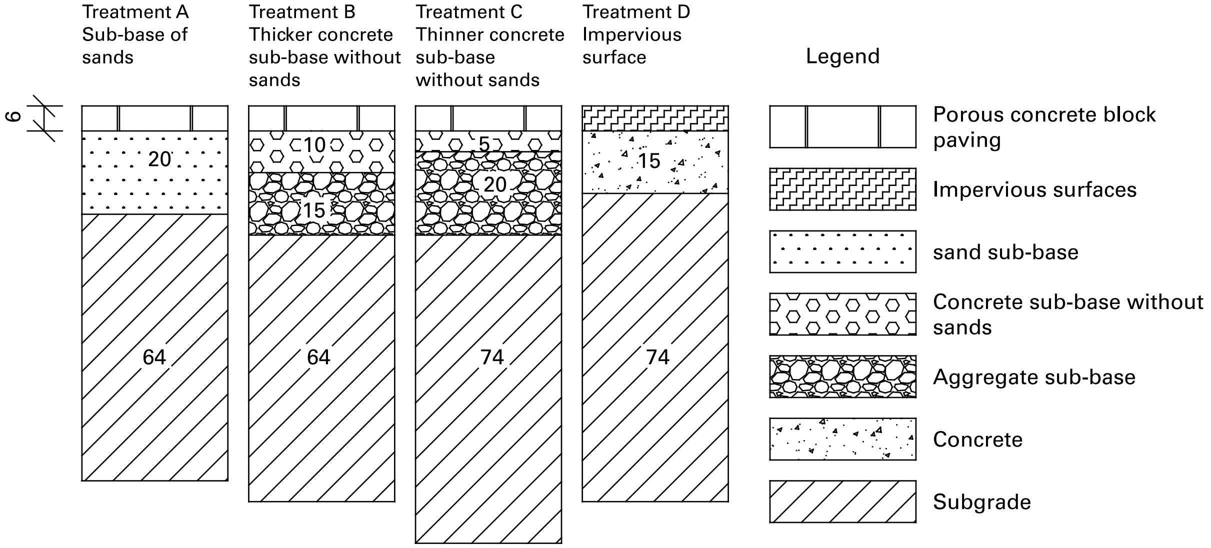

Figure 2 | Typical cross section of porous pavement and impervious pavement. The thickness unit is the centimetre.

sub-base stone type. Gravel (5–10 mm), sand and concrete lacking sand were placed in each reservoir, which separated the sub-base reservoir from the concrete blocks and the bedding gravel on which they were laid (Figure 2). The aggregate sub-base and sand sub-base were constructed with a relative density $D_r = 0.70$. After 72 h of paving, concrete lacking sand was sampled through a super light-weight core drill, capable of drilling 5–10 cm depth into the concrete (see Table 1).

Water movement (flow rates and volume) within the pervious construction is determined by the porous nature of the materials. Materials included mixtures of widely ranging particle sizes (continuously graded) to closely graded, near-single-sized particles (single size grading). Continuously graded soils tend to be more densely packed, with the smaller particles filling in voids, producing a more rigid but less permeable medium. Conversely, single-sized materials with a limited range of sizes have relatively large open voids, which provide a higher permeability with greater storage but less rigidity.

The volumetric dimensions of the porous concrete block paving are $100 \times 200 \times 60\,\text{mm}^3$, the pressure intensity 44.3 MPa, the porosity 7.45% and the infiltration coefficient 0.789 mm/s. The pavement surfaces were graded to a slope between 1–2%.

As Table 1 shows, surface materials like porous concrete and aggregate sub-base generally had infiltration rates that greatly exceed the designed rainfall intensity.

Experiment methods

The artificial rainfall events are presented in Table 2. The return period was selected in accordance with the guidelines outlined by the Ministry of Construction, PR China. Rainfall infiltration was calculated according to the Horton approach (Wolfram & Chris 2002).

Four pairs of TDR probes (type 6050X1Trase, Aozuo Ecology Instrumentation Ltd) were arranged in each cells' subgrade. The horizontal distance between two pairs was 100 cm and the average value was adopted as the soil water content. The distance between the top-layer probes and designed subgrade surface was 10 cm and the vertical distance between each pair was 15 cm.

Four artificial rainfall events were recorded during the monitoring period (Table 3). Runoffs from the different porous pavement treatments from the surface and drainage under the cells were collected through the plastic pipe constructed across the head of the cells. The start and end of runoff, and the start and end of drainage that percollated through the subgrade were all recorded.

Table 1 | Physical analyses of experimental materials

Material (subgrade)	Limit of liquid (%)	Limit of plasticity (%)	Plasticity index (%)	Compress coefficient (MPa)$^{-1}$	Compress index (MPa)	Maximum density (g/cm^3)	Saturated water content (cm^3 cm^{-3})
Light loam	28.8	15.5	13.3	0.069	23.613	1.77	0.399
Material (sub-base)	Maximum density (g/cm^3)		Minimum density (g/cm^3)	Relative density	Density (g/cm^3)		Porosity (%)
Sands	1.91		1.37	0.70	1.71		38
Material (sub-base)	Thickness (cm)	Intensity of pressure (MPa)	Bending strength (MPa)	Infiltration coefficient (mm/s)	Porosity (%)	Standard	
Concrete lacking sands	10	12.27	1.22	12.6	8.46	JC/T446-2000 and DL/T5150-2001	
	5	13.3	2.45	10.7	18.8		

Table 2 | Conditions of artificial rainfall

Number	Date (dd/mm/yy)	Period of rainfall (min)	Precipitation (mm)	Return period (yr)
N6	26/08/04	60	59.36	6
N100-1	06/09/04	120	118.72	100
N2	21/09/04	40	39.57	2
N20	21/10/04	120	94.09	20
N100-2	26/04/05	120	118.72	100

RESULTS AND DISCUSSION

Effect of different treatments on runoff

Surface runoff and infiltration rates were measured at the experimental station in 2004 and 2005. The experiment was carried out during the summer months, with most precipitation occurring in that season in Beijing.

A comparison of precipitation rates and surface runoff for the three porous pavement cells and the impervious surface cell during a storm beginning at 16:30 on 26 August 2004 is shown in Figure 3. There was no measurable continuation of runoff on the Treatment B surface during the rainfall process. Runoff on the impervious surface cell closely followed precipitation rates during all rainfall events. Minor surface runoff from the porous surface cells beginning around 50 min into the event was attributed to leaks in the different sub-bases used to capture water, which would infiltrate into the subgrade soil. The phenomenon can be attributed to the storage capacity of the porous pavement, which delays evacuation of water into the runoff

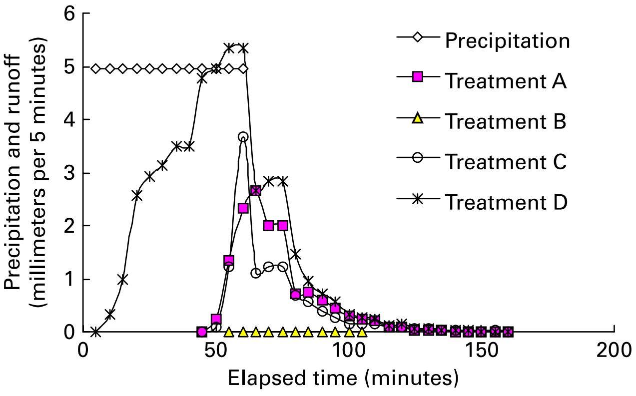

Figure 3 | Comparison of precipitation rate, surface runoff of three porous pavement cells and the impervious surface cell.

Table 3 | Data of different treatments obtained from outflow monitoring

	Rain event date (dd/mm/yy)	Recorded rainfall (mm)	Rainfall duration (min)	Surface runoff start (hh:mm)	Surface runoff end (hh:mm)	Recorded runoff (mm)	Drainage start (hh:mm)	Drainage end (hh:mm)	Drainage volume (mm)	Outflow percentage (%)
A	26/08/04	59.36	60	0:45	3:00	14.14	1:49	256:45	5	23.8
B	26/08/04	59.36	60	–	–	0	1:49	187:15	14.84	0.0
C	26/08/04	59.36	60	0:45	3:00	11.28	9:30	31:30	0.63	19.0
D	26/08/04	59.36	60	0:06	3:00	50.7	2:00	15:45	0.45	85.4
A	06/09/04	118.72	120	0:40	3:05	79.41	2:08	104:30	3.3	66.9
B	06/09/04	118.72	120	1:10	2:08	47.8	2:08	139:00	17.37	40.3
C	06/09/04	118.72	120	0:35	2:20	81.38	8:00	237:30	1.08	68.5
D	06/09/04	118.72	120	0:05	3:00	116.16	2:08	11:00	0.39	97.8
A	21/10/04	94.09	120	0:42	2:15	44.18	2:25	68:30	1.45	47.0
B	21/10/04	94.09	120	1:16	2:08	23	2:18	149:30	18.87	24.4
C	21/10/04	94.09	120	0:45	2:10	49.45	21:30	260:00	2.87	52.6
D	21/10/04	94.09	120	0:05	2:50	93.84	2:30	16:00	0.23	99.7
A	26/04/05	118.72	120	0:40	2:35	44.08	2:35	89:35	1.29	37.1
B	26/04/05	118.72	120	1:10	2:05	26.56	2:25	152:05	20.98	22.4
C	26/04/05	118.72	120	0:45	2:20	44.6	8:35	211:05	5.07	37.6
D	26/04/05	118.72	120	0:02	3:05	110.31	2:25	17:05	0.23	92.9

outlet. This delaying effect also renders the evacuation a more gradual process, as reflected by both the reduction in maximum runoff rates measured at the runoff outflow and by the increase in time required for discharge. The discharge duration for the Treatment A surface exceeds 10 d. As expected, experimental results showed less measured surface runoff from the porous pavement areas. Infiltration capacity of all three tested porous pavement systems was better than the traditional impervious surface.

For the porous pavements with the three different sub-base materials, the initial loss, the runoff coefficient and the percentage runoff on average varied, with Table 3 summarizing results. For the rainfall amount/duration of 118.72 mm/2 h, the runoff outflow percentages of Treatments A, B and C ranged from 22.4 to 68.5, but for Treatment D it was 92.9–97.8. For the rainfall amount/duration of 94.09 mm/2 h, the incidence of runoff for Treatment B was 71 min later than the impervious pavement, with a recorded flow volume of just 23.00 mm. For the rainfall amount/duration of 59.36 mm/h, the incidence of runoff for the porous pavement surface was 45 min later than the impervious pavement, with the flood peaks reduced by 35–100%, especially for Treatment B, with a recorded flow of zero.

The order of infiltration coefficients for the different media investigated in this study is $K_{\mathrm{CLS}} > K_{\mathrm{PCBP}} > K_{\mathrm{S}} > K_{\mathrm{IS}}$, where K_{CLS}, K_{PCBP}, K_{S} and K_{IS} are the infiltration coefficients for the materials of concrete lacking sand, porous concrete block paving, subgrade and impervious surface, respectively (see Figure 2). The factors discussed above explain the quantitative relationships of flood peak for the four surfaces $F_{\mathrm{D}} > F_{\mathrm{C}} > F_{\mathrm{A}} > F_{\mathrm{B}}$, where F_{D}, F_{C}, F_{A} and F_{B} signify the volume flood peaks for Treatments D, C, A and B, respectively.

Soil moisture of subgrade

The soil moisture of Treatment A measured at different depths on 26 August 2004 is shown in Figure 4. 30 min after rainfall occurred, the soil water content began to increase, with the soil saturating from top to bottom as infiltration progresses. After spraying for 60 min, the water content at 0–40 cm depth increased significantly, especially at depths ranging from 0–25 cm. The infiltration process for the porous pavement can be divided into two distinct phases. In the first phase, the runoff rate was reduced by the porous surface. This is because the porous surface increased rainfall infiltration and water was stored in the sub-base, with the result that rainstorm water logging was delayed. In the second phase, because of water storage in the sub-base, the infiltration formed subsurface flow in the porous concrete block paving and sub-base which increase infiltration into the subgrade after rainfall.

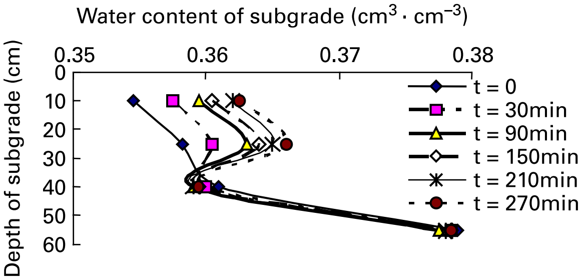

Figure 4 | Infiltration curves of subgrade in Treatment A.

The porous concrete block paving and sub-base foster conditions for subsurface flow. Although the last heavy rainfall occurred 20 d ago, its infiltration into the subgrade soil continued after the last rainfall on account of subsurface flow. Additionally, the higher the soil density, the lower the soil infiltration rate (Wu *et al.* 2003). Because the subgrade density of the porous pavement was high (1.593 g/m^3), water in the subgrade moved very slowly. Water content in the top subgrade was low, while water content at 55 cm depth was high, because soil moisture had not discharged from the cell bottom completely, with similar results presented by Wen *et al.* (1991) and Huang (2000). When soil texture layers form, evidently the subsurface flow volume can be accommodated. It flowed horizontally in the surface layer. Its velocity was low.

Drainage under the cells of different treatments

Table 3 shows that drainage under the Treatment B cell was 18.87 mm when the precipitation amount/duration was 94.09 mm/2 h, the largest value of the four treatments. Its drainage duration reached 149.5 h, demonstrating that the attenuation effect is very significant. This is because the water movement through the porous concrete block paving and sub-base exists as fluid flow through pores. The pore velocity is high, with the hydraulic head pressure higher on the subgrade surface producing higher rainfall infiltration rates into the subgrade. In addition, there is a lag phenomenon of drainage for the three porous pavements, particularly for Treatment C, exceeding 10 d. Figure 4 also shows that the infiltration was localized between 0 and 40 cm and this can be attributed to surface evaporation, producing low water content in the top subgrade before this rainfall. Because the subgrade permeability is low (2.28×10^{-4} mm/s), water infiltrated into the subgrade very slowly in the first 270 min. Therefore, the water content in the top soil horizon between 0 and 40 cm increased, and new water did not infiltrate beyond 40 cm depth, resulting in an unequal vertical distribution of water content (Qin 2003).

Effect of preceded rainfall on runoff

The infiltration capacity of the ground depended on both the permeability of the soil and the actual water content which in turn affects hydraulic conductivity. The effect of porous pavements on reducing runoff is shown in Figure 5. Before 6 September 2004, there was one precipitation event of 59.36 mm/h on 26 August 2004. There was no artificial rainfall for half a year before 26 April 2005. The two rainfalls on 6 September 2004 and 26 April 2005 had the same precipitation of 118.72 mm/2 h. A comparison between the two curves (Figure 5) indicated that the volume of runoff on 6 September 2004, preceded by 10–11 d of precipitation, was significantly higher than that of no rainfall. From the curves, it can be seen that, for the uniform pavement treatment, the runoff preceded by

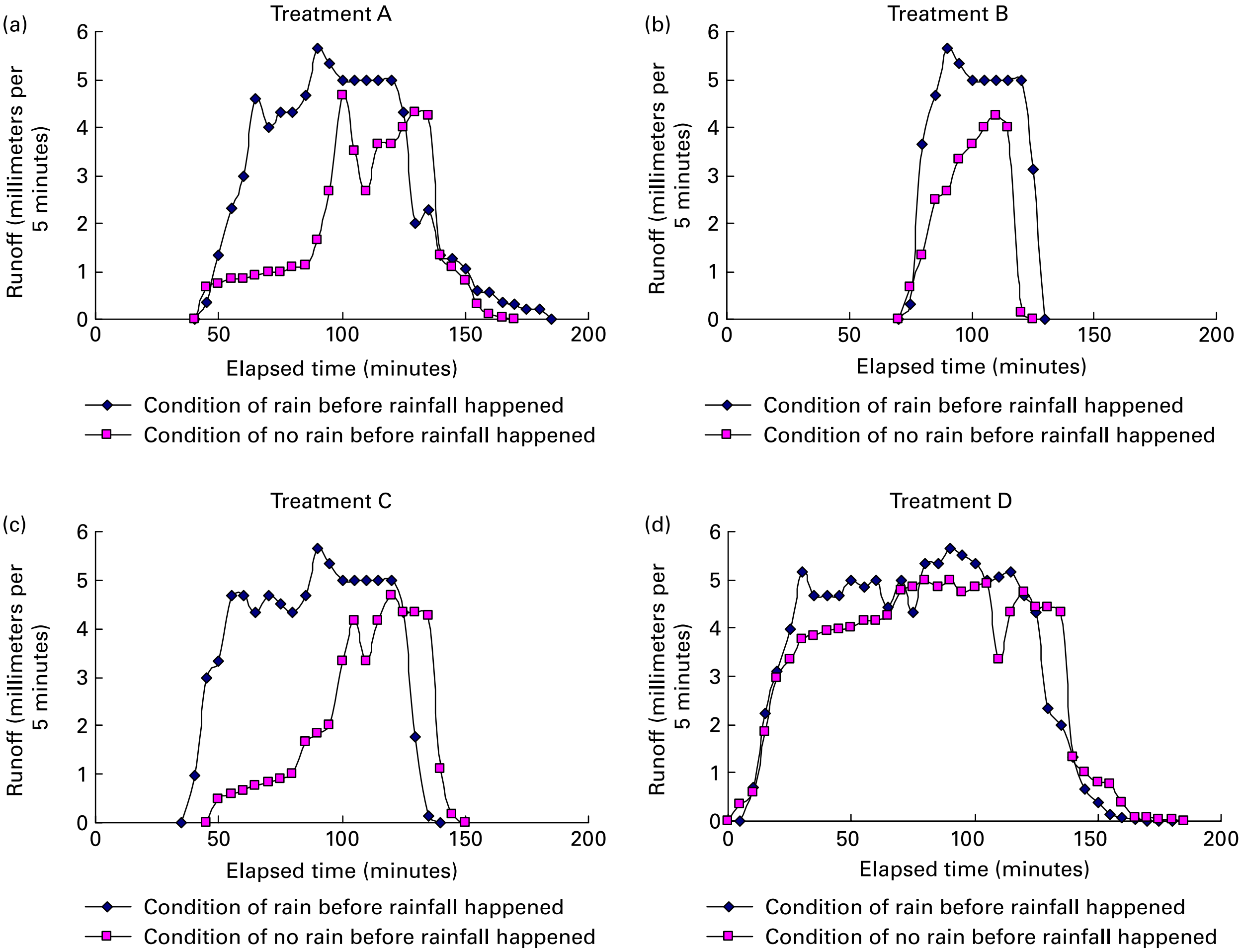

Figure 5 | Runoffs of different treatments under conditions with rainfall and without rainfall before artificial rainfall happened.

a period of no rainfall was 5–10 min later than a period preceded by rainfall, with the flood peak decreased by 5% or more. There was no obvious difference of Treatment D between preceded rainfall events and non-preceded rainfall events.

During the infiltration process, infiltration rates were affected by negative soil pressures before saturation. The lower the initial water content, the higher the grades of radical potential and soil suction. The soil water content following periods of no rainfall was lower and the porous pavement function of reducing runoff was distinct. So, conditions with rainfall and without rainfall had different effects on the next rainfall infiltration and runoff.

From Figure 5, it can be seen that Treatment B had runoff beginning later and terminating earlier, with the shortest runoff time period of the three porous pavement systems for the same rainfall. With regard to Treatment D, runoff yield occurred with the inception of precipitation. The results demonstrate that the sub-base of Treatment B is the most effective surface for minimizing runoff by maximizing infiltration.

Effect of different rainfall intensities on runoff

Rainfall intensity is another predominant factor in determining the cause of runoff. The higher the precipitation accumulation, the higher the runoff. Consequently, to avoid ground rainstorm water logging, the infiltration rate through the surface must exceed the maximum rainfall intensity. The effect of different rainfall intensities on runoff for the four surfaces is presented in Figure 6. Compared to the impervious pavement, runoff on porous pavements is delayed. Of the four surfaces, Treatment B reduced runoff most significantly. For the same rainfall, the runoff of the porous pavement was smaller than that of the impervious surface.

Excessive runoff generation can damage the ground surface. When precipitation had satisfied rainfall

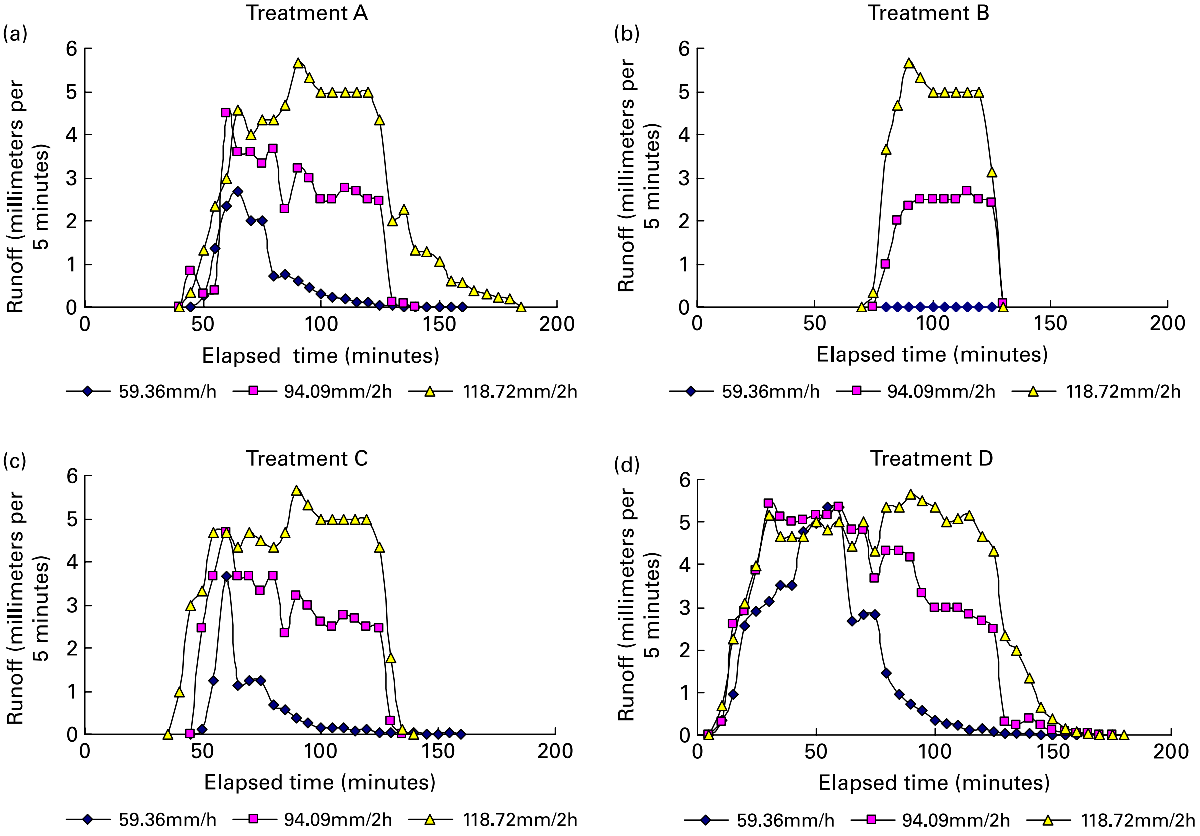

Figure 6 | Runoffs of different treatments in three rainfall intensities.

interception in a low-lying place, the rainfall intensity exceeded infiltration, causing ground rainstorm water logging and the incidence of runoff (Wen *et al.* 1991; Zhu & Jin 1991). With respect to rainfall which had a higher and narrower symmetrical flood peak, and a shorter duration, rainfall intensity was the most dominant factor, and the influence of water content was not important in many cases (Wen *et al.* 1991). The diameter, the final velocity and the kinetic energy of the raindrops increase with increasing rainfall intensity. Consequently, the scouring force on the ground surface increases, as well as runoff on porous pavements.

CONCLUSIONS

This study evaluated the performance of three porous pavement systems from the perspective of infiltration and runoff, with very positive performance in comparison to a traditional impervious surface.

All three porous pavement surfaces increased infiltration and decreased runoff. Larger porosity values, higher infiltration coefficients, thicker sub-base layers and lower initial water contents of the subgrade produce higher infiltration rates and smaller runoff coefficients.

When rainfall infiltrates into a porous surface and its underlying sub-base, the outflow hydrograph will be influenced by the way in which the construction materials retain or delay flow. The quantitative relationship of runoff coefficients for the different media investigated in this study were: $R_D > R_C > R_A > R_B$, where R_D, R_C, R_A and R_B signify runoff coefficients of Treatments D, C, A and B, respectively. The optimal sub-base for reducing runoff by increasing infiltration was B. It had a thickness of 31 cm, consisting of a 6 cm top layer of porous concrete and a 25 cm sub-base, consisting of 10 cm concrete without sand and a 15 cm aggregate base. Under a rainfall rate of 59.36 mm/h, the runoff coefficient of Treatment B was 0 compared to the coefficient of 0.85 for the impervious pavement.

Sediment and sediment-associated pollutants will tend to be trapped within the upper layers of the construction above the sub-base stone. The accumulation of material diminishes the rate of infiltration of stormwater and ponding of surface waters will eventually occur. The pavements in the Shuangzi Garden in Beijing, where the above porous pavements were installed in 2001, still have measured infiltration rates in excess of 1.58 mm/s in 2005, despite receiving no maintenance over that period. When the surface layers become too blocked to permit acceptable infiltration rates, the concrete blocks will be lifted and the bedding gravel excavated and landfilled. It is estimated that such reconstruction to restore the permeable surface may be necessary every 15–18 years.

Despite these generally favourable results, uniformly good performance cannot be guaranteed for all locations or even time periods. The highest rainfall intensity observed during the study was 59.36 mm/h. Our extremely positive infiltration results may not apply to other locales that receive higher rainfall intensities. In addition, the study excluded extended periods of sub-freezing weather, so it is not a comprehensive evaluation of the suitability of such systems for all climate zones and all weather conditions. Economic considerations, such as the cost of installing porous pavement systems or the cost savings from reduced stormwater management facilities, will play a major role in determining the feasibility of any given project. Despite these acknowledged limitations, we believe that these results provide a clear indication of the value of porous pavement systems for broad expanses of the human engineered environment.

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REFERENCES

Benedetto, A. 2002 A decision support system for the safety of airport runways: the case of heavy rainstorms. *Transport. Res. A-pol.* **36**, 665–682.

Field, R. 1985 Urban runoff: pollution sources, control, and treatment. *Water Res. Bull.* **21**(2), 197–206.

Huang, X. Q. 2000 *Hydrology*. Higher Education Press, Beijing.

Klein, R. D. 1979 Urbanization and stream quality impairment. *Water Res. Bull.* **15**(4), 948–963.

Konrad, C. P., Booth, D. B., Burges, S. J. & Montgomery, D. R. 2002 Partial entrainment of gravel bars during floods. *Water Res. Res.* **38**(7), 1104.

Nelson, E. J. & Booth, D. B. 2002 Sediment sources in an urbanizing mixed land-use watershed. *J. Hydrol.* **264**(1–4), 51–68.

Pratt, C. J. 1995 A review of source control of urban stormwater runoff. *Water Environ. Manage.* **9**(2), 132–139.

Pratt, C. J. 1999 Use of permeable, reservoir pavement constructions for stormwater treatment and storage for re-use. *Water Sci. Technol.* **39**(5), 145–155.

Pratt, C. J. 2002 *Source Control Using Constructed Pervious Surfaces*. CIRIA, London.

Pratt, C. J., Mantle, J. D. & Schofield, P. A. 1989 Urban stormwater reduction and quality improvement through the use of permeable pavements. *Water Sci. Technol.* **21**(8/9), 769–778.

Qin, Y. D. 2003 *Soil Physics*. Higher Education Press, Beijing.

Trimble, S. W. 1997 Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* **278**(21), 1442–1444.

Wada, Y., Miura, H., Tada, R. & Kodaka, Y. 1997 Evaluation of an improvement in runoff control by means of a construction of an infiltration sewer pipe under a porous asphalt pavement. *Water Sci. Technol.* **36**(8/9), 397–402.

Watanabe, S. 1995 Study on storm water control by permeable pavement and infiltration pipes. *Water Sci. Technol.* **32**(1), 25–32.

Wen, K., Jin, G. S., Li, D. J. & Li, Q. 1991 *Mathematics Simulation of Runoff*. China Water Power Press, Beijing.

Wolfram, S. & Chris, J. 2002 Modelling the outflow from a porous pavement. *Urban Water* **4**(3), 245–253.

Wu, F. Q., Zhao, X. N. & She, D. 2003 Analysis on affecting factors of soil infiltration in slope farmland. *Bull. Soil Water Conserv.* **23**(1), 16–18.

Zhu, Y. S. & Jin, G. Y. 1991 *Urban Hydrology*. China Technology Press, Beijing.

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