Pollution Retention Capability and Maintenance of Permeable Pavements

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Abstract

Permeable pavements of concrete paving-stones for rainwater infiltration are established as a sustainable method for the drainage of traffic areas and for pollutant source control. Various systems for different applications exist. Pollutants like heavy metals and hydrocarbons in the runoff can endanger soil and groundwater, when the they are not sufficiently removed during infiltration. Clogging and the decrease of infiltration capacity are problems that must be considered if permeable pavements are demanded to be used as an alternative to traditional drainage systems. In this study the pollution retention capacity of different permeable road constructions is assessed in the laboratory and in field investigations. A new cleaning device to recover the infiltration capacity was developed, that ensures a lifetime operation of the investigated pavements. With special designed concrete pavers a sufficient protection of soil and groundwater can be achieved. The use of permeable pavements is sustainable, if planning, construction supervision and maintenance are carried out according to the latest research results.

1 Introduction

Permeable pavements with reservoir structure of concrete paving-stones offer the possibility for a decentralized, sustainable stormwater management and source control in urban areas. Especially, runoff from streets and parking areas with low traffic densities can be infiltrated to support groundwater recharge and to reduce hydraulic stress in sewer systems, receiving waters and wastewater treatment plants. Infiltration can help to return the urban water cycle to its natural condition, increasing groundwater recharge and evapotranspiration.

But runoff from streets and car parks contains pollutants like heavy metals and hydrocarbons that can endanger soil and groundwater. Furthermore, particles in the runoff provoke clogging, so that surfaces must be cleaned to recover infiltration capacities from time to time. This study shows the pollutant retention capacity of permeable pavements under laboratory and field conditions and assesses a new cleaning device, that was developed to recover infiltration capacities in the case of clogging.

2 Problem Identification

The permeable construction of pavements with concrete pavers requires specific knowledge and high manufacturing quality. The main problems are:

- Traditional roadbeds are not designed to store and transport water. The objective of the subbase is to remove water as quickly as possible to prevent structural damage of the pavement.

- The bearing capacity of the roadbed must be as high as the bearing capacity for traditional pavement systems, even during rain events.
- Porous paving-stones show a higher risk of abrasion and damage because of their porous structure.
- Deicing salts and frost may damage the pavement during winter time. Porous concrete is especially sensitive to frost because of its open pores.
- Pollutants in the runoff can endanger soil and groundwater if they are not removed during infiltration. Especially heavy metals and hydrocarbons like oils from spillage and polycyclic aromatic hydrocarbons by combustion of engines must be retained in the pavement.
- Permeable pavements are sensitive to clogging. Suitable and cost effective cleaning methods must be developed that ensure a sufficient infiltration capacity.

3 Objectives

The main objective of the study presented is to determine the behaviour of pollutants in the pavement, the roadbed and the soils below the pavements. Laboratory studies in test-rigs and field investigations were carried out. Clogging effects were measured and a cleaning device was developed, that allowed the recovering of the infiltration capacity of the existing pavement. The concentrations of heavy metals and mineral oils, which are the most important harmful substances on traffic areas, are determined in the whole structure and in the underlying soil. If pollutants migrate through the structure, their concentrations are expected to be increased in the roadbed and the underlying soil.

3.1 Systems of Permeable Pavements

Four different types of permable pavements are frequently used nowadays. The first type consists of concrete pavers with wide joints or apertures to infiltrate the water into the underground. For this investigation a system with canals on the sides of the paving stones were chosen (see Figure 1a). The joints of these pavers are filled with a permeable mineral material that allows a rapid water-transport. By the use of these canals the pavers only need narrow joints (suitable for shopping-trolleys). This pavement visually resembles typical impervious.

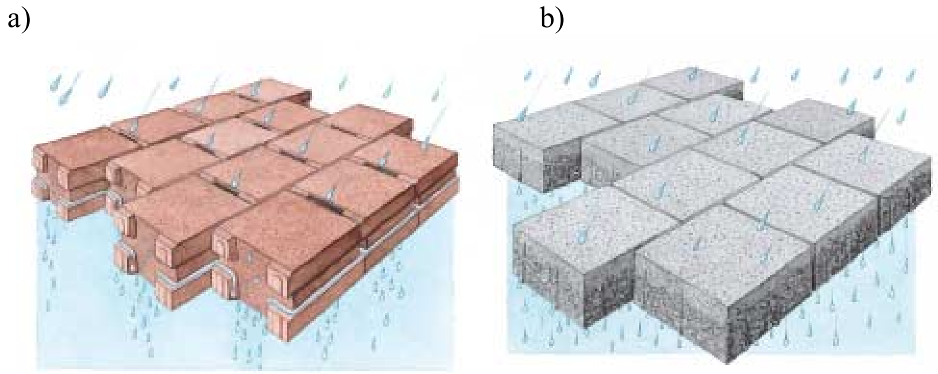

Figure 1. systems of permeable pavements, a) pavers with canals and b) porous pavers

High pollution retention capacities can be achieved with paving-stones of a special porous concrete (DIERKES 1999). The investigated system consists of a porous paver with two layers (see Figure 1b). The top, fine layer acts as filter for pollutants. The high porosity enables a sufficient infiltration capacity and gas exchange with the underlying soil. Particulate matter from the rain, the atmosphere and the vehicles is trapped in the upper 2 cm of the paver and can be removed by cleaning.

The third system consists of porous paving-stones with greened apertures. This system is suitable for all areas, where a natural look is desired. The small apertures of 3 cm x 3 cm are filled with a specific substrate that stores water, so that the grass does not dry out during rain-free periods. The open structure of the pavers prevents over-heating of the pavement and is an ideal growth environment for grass (see Figure 2a).

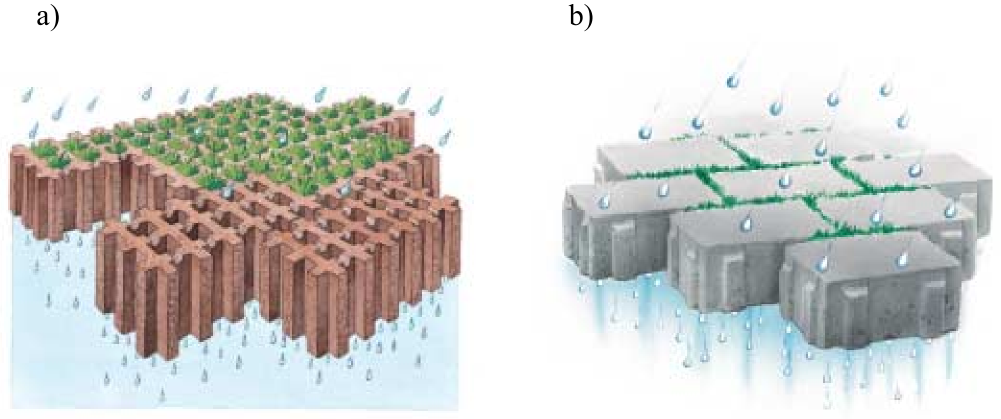

Figure 2. systems of greened permeable pavers, a) small apertures, b) wide joints

The last presented system is made of concrete pavers equipped with spacers, that ensure a large joint during construction. These joint are also filled with a substrate that stores the rainwater and provides it to the grass during dry periods (see Figure 2b).

3.2 Physical Behaviour of the Presented Pavements

Paving stones of concrete must fulfill strict requirements concerning pressure resistance and resistance against frost and deicing salts. For permeable pavements, the infiltration capacity must be high enough to infiltrate even the strongest rain events. The superstructure of permeable pavements must have a suitable bearing capacity when water is stored temporarily in the subbase. Requirements must be controlled regularly during porous pavement manufacturing to ensure a high quality standard.

The average pressure resistance of paving stones must be ≥ 60 N/mm^2 (DIN 18501, 1982). No single paver in the test must have a resistance smaller than 50 N/mm^2. The pressure resistance of porous concrete pavers is smaller, so that 45 N/mm^2 must be reached.

The resistance against frost and deicing salts is tested by specification AWT-101 of the Wilhelm Dyckerhoff-Institute. For this test 25 frost/melt changes are simulated and the paving-stones must not be damaged by the procedure.

Permeable pavements in Germany must ensure an infiltration capacity of ≥ 270 l/(s·ha) according to the memorandum for permeable constructions (FGSV 1998) that equals a hydraulic conductivity of $2{,}7 \cdot 10^{-5}$ m/s. The worksheet A 138 of the German Wastewater Association "Planning, construction and operation of stormwater infiltration devices" (ATV

2000) takes into account regional rain statistics from the German Weather Service. This data shows that 270 l/(s·ha) are not always necessary to infiltrate the total amount of rainwater.

The bearing capacity of the subbase for permeable constructions depends on the subbase material. The design is done according to the regulations for the standardization of roadbeds (FGSV 2001).

The bearing capacity of the materials can be tested in the laboratory with the CBR-test (FGSV 1998). A CBR-value of at least 50 % after four hours of water storage must be fulfilled. In this case the bearing capacity is sufficient.

3.3 Legal Requirements

Stormwater infiltration in Germany is required by law. Since the beginning of the 90´s the rainwater of new developed private properties cannot be discharged into the public sewer. The total amount of rainwater in most of the states must be kept on the property and infiltrated to the groundwater or discharged into receiving water. Promotion programs by the local water authorities support the disconnection of sealed areas to the sewer systems. Wastewater fees were split into wastewater and rainwater fees. So it is cost effective not to discharge the rainwater into the sewer system.

On the other hand the German law for the protection of soil and groundwater contains strict limits for infiltrated waters at the transition to the saturated zone. These limits are lower than limits for drinking water quality for some constituents. Pollutants in stormwater must be removed if the infiltration devices is to fulfill regulatory requirements.

3.4 Experimental methodology

The presented study consists of three parts. In the first part, laboratory experiments were carried out that show the behaviour of different permeable pavements and their pollution retention capabilities. In the second part, one system was investigated in a field study. The first porous pavements were built 15 years ago and were investigated for their pollutant concentrations. In the third part of the study, a newly developed cleaning device was tested that allows for the recovering of the infiltration capacity of porous pavement nearly to its initial state.

4 Laboratory experiments

The laboratory investigations were carried out in test-rigs. The rigs consist of stainless steel and have dimensions of 40 cm in length and 60 cm in height (see Figure 3). The rigs are loaded by a sprinkler made of injection-needles. Runoff is pumped into the sprinkler by a peristaltic pump. The volume of water is measured by flow-meters. At the bottom of the test-rigs the seepage is collected and sampled. PH, redox potential and electric conductivity are measured online during the tests. All data is recorded by a PC.

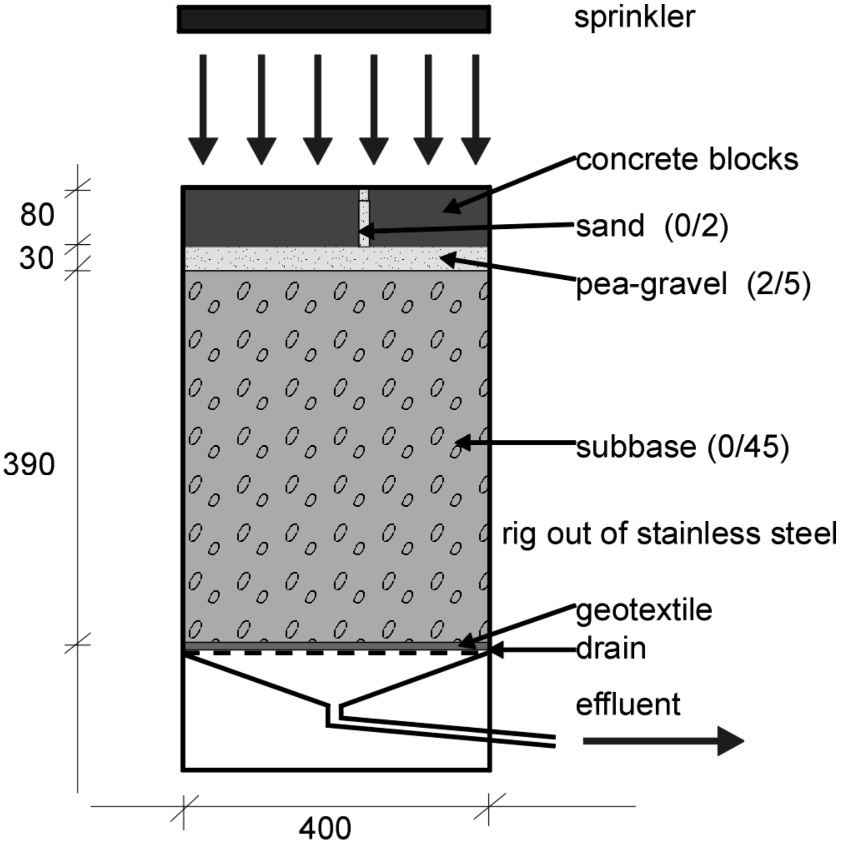

Figure 3. Test rig filled with a porous pavement with reservoir structure complying to German regulations

The rigs are loaded with a synthetic runoff at a *pH* of 5, that is spiked with dissolved heavy metals. The concentrations were chosen from literature data and were multiplied by 10 to study the structure under worst case conditions. Altogether 4000 mm of rain were simulated, reflecting 5 years of rain in Germany.

4.1 Pollution Retention Capacities of Different Pavers

Four different types of concrete pavers, a paver with open joints, a porous paving-stone, a paver with large greened apertures and a porous paver with greened apertures were tested for their retention capability for dissolved heavy metals (see Figure 4). The tests were carried out with intermittent rain events at an intensity of 144 mm/h. The high intensity should simulate a worst case scenario. The rigs were charged with synthetic rainwater containing mean concentrations of 180 µg/l Pb, 470 µg/l Cu, 660 µg/l Zn and 30 µg/l Cd and *pH* was at 4.9. According to the concentrations in the synthetic runoff and in the seepage a mass balance for the metals was calculated. In the diagram one can see the loads of metals for one square-meter over a period of 50 years. The left columns show the total input mass of metals and the right columns show the mass of metals that left the different types of permeable pavements. There are big differences in the ability of the pavers and joint fillings to trap the heavy metals. Most metals in seepage were found where the infiltration was carried out only through the joints. Blocks with greened areas seem to be very efficient at trapping metals. Lead and copper were retained more effectively than zinc and cadmium in the structure.

In conclusion, paving stones of porous concrete and greened apertures showed the highest pollution retention capacities. Pavements with large joints or apertures for infiltration must be equipped with a suitable joint filling, otherwise pollutants can pass the pavement and get into the underground more easyly.

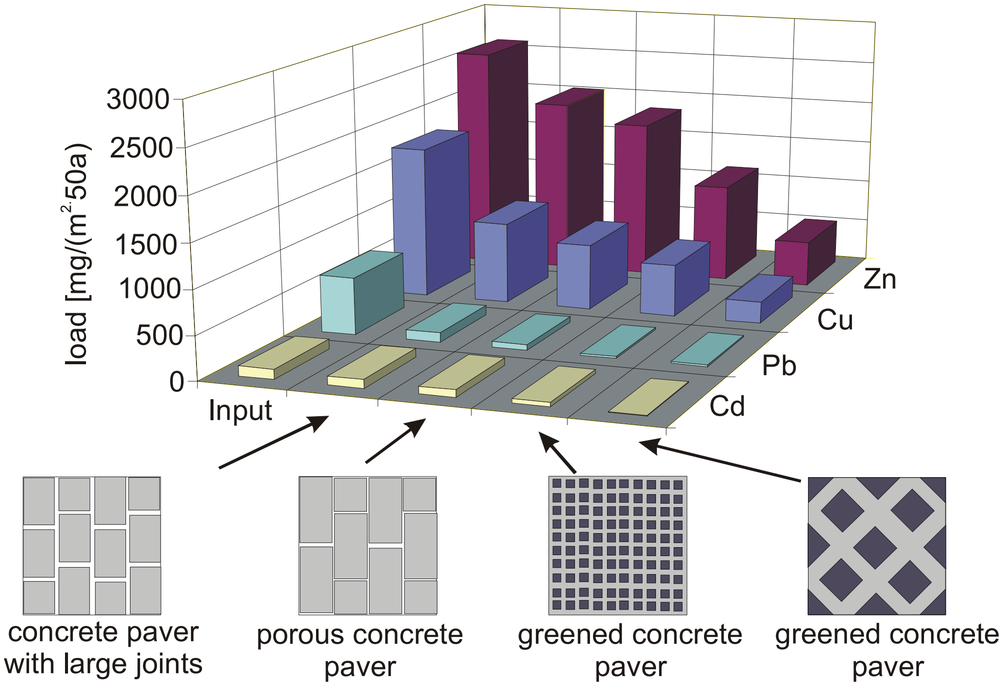

Figure 4. Heavy metals retention of four different permable pavements

4.2 Pollutant Retention Capacities of Different Subbase-Materials

The porous blocks were used for investigations of total road build-ups. Four different subbase materials, limestone, basalt, sandstone and gravel were tested. The investigations were carried out simultaneously with the investigations of the pavements. In the rigs four different materials were investigated. Each material fulfils regulations for road-construction in Germany. Proctor-densities are between 2,07 g/cm^3 and 2,17 g/cm^3. *PH* is between 8.3 and 8.8. The measured hydraulic conductivities vary from $3\cdot10^{-4}$ m/s (gravel) up to $2\cdot10^{-2}$ m/s for the sandstone. The limestone is situated in the middle of the conductivities. The concentrations of Pb, Cu, Zn and Cd were in the range of natural soils. In the effluent at the beginning of the tests *pH* was at 8,0 at all rigs, except of the basalt with a *pH* of 8,7. At the end of the tests *pH* has lowered to 7,3 in the sandstone rig, up to 8,0 in the basalt rig. Red-Ox-Potential in the effluent was between 235 mV and 240 mV. So after the infiltration of 4000 mm of rain effluent was still in an intermediate *pH*-range and red-ox was high, so there are no indications for high metal mobility. Cadmium-concentrations in the effluent rose linearly during the tests. In the basalt rig and in the gravel rig they could not be detected after 4000 mm of rain. In the limestone rig cadmium reached the limit for seepage-water of 5 µg/l after about 3000 mm. In the column with the sandstone the limit was decreased after about 1000 mm. Copper concentrations in effluent were rising at the beginning of the tests and stay at one level after about 1500 mm. For the basalt and the gravel about 15 µg/l to 20 µg/l were detected. In the rigs with the limestone concentrations reached about 30 µg/l to 40 µg/l, and at the sandstone column concentrations of about 60 µg/l were analysed. So in the sandstone the limit of 50 µg/l is surpassed. Zinc and lead-concentrations were found to be very low. Lead was not detected in effluent. Zinc was detected in concentrations up to 300 µg/l in the sandstone-rig. All mean concentrations of effluents of the tests are shown in table 1. The main reason for the different behaviour of the materials is connected to the part of grains smaller than 2 mm. The results from the pilot-scaled test look very similar to the rigs. Here the concentrations in the effluent were even lower, because of lower the rain-intensities used for infiltration.

Table 1. Concentrations of metals in the synthetic runoff and in the effluent of the test rigs, percentage of metals retained in the columns after infiltration of the loads of about 50 years and permissible limits for seepage after the German regulations

	lead	cadmium	copper	zinc
synthetic runoff	180 µg/l	30 µg/l	470 µg/l	660 µg/l
effluent (mean conc.)				
gravel	< 4 µg/l	0,7 µg/l	18 µg/l	19 µg/l
basalt	<4 µg/l	0,7 µg/l	16 µg/l	18 µg/l
limestone	< 4 µg/l	3,2 µg/l	29 µg/l	85 µg/l
sandstone	< 4 µg/l	10,5 µg/l	51 µg/l	178 µg/l
retention				
gravel	98 %	98 %	96 %	97 %
basalt	98 %	98 %	96 %	98 %
limestone	98 %	88 %	94 %	88 %
sandstone	89 %	74 %	89 %	72 %
limits for seepage	25 µg/l	5 µg/l	50 µg/l	500 µg/l

4.3 Conclusions

Permeable pavements appear to be effective at trapping dissolved heavy metals in runoff. Most metals are precipitated in the upper 2 cm of the porous concrete (DIERKES et al. 1999). But *pH* in effluent shows, that the buffer capacities of the concrete are very high, so that there is no danger of a mobilisation. In the subbase higher concentrations of metals were found to a depth of 20 cm for cadmium and lead and to a depth of 10 cm for copper and lead after simulating 50 years of operation. Metal concentrations in the effluent only reach the permissible limits at cadmium and copper, when very coarse material for the subbase is used. Most structures show no danger of a possible groundwater contamination during the tests, so porous pavements made of concrete blocks could be used without fear of a breakthrough of metals for a period of at least 50 years.

5 Field Study

The field study was carried out on a parking area of a supermarket in Stadtlohn, Germany. The parking lot shows a very high daily frequency of vehicles. The pavement consists of porous concrete stones without filter layer. The infiltration capacity of the pavement was determined with a drip-infiltrometer. A steel-ring with a diameter of 500 mm was cemented onto the pavement (see Figure 5a).

Figure 5. a) Measuring infiltration capacity with a drip-infitrometer, b) the parking area of a supermarket in Stadtlohn

With a sprinkler the test area was rained. The rain intensity was controlled by a flow meter. Water level in the ring is regulated between 1 mm and 3 mm. The infiltrated volume of water is protcolled over the time and equals the infiltration capacity.

After the determination of the infiltration capacity, one parking box was selected, that showed a very high content of spilled oil on the surface. The pavers of this box were removed and the whole subbase was dug out. Samples were taken of the pavers, the filling of the joints, the bedding, the crushed stones of the subbase and the soil up to a depth of 30 cm. Alls samples were investigated for concentrations of lead, copper, zinc, cadmium, mineral oil type hydrocarbons (MOTH) and polycyclic aromatic hydrocarbons (PAH).

5.1 Results

The pavement of the car park consists of the porous pavers with the joint filling (1 mm to 3 mm), a bedding with a depht of 5 to 8 cm (2 mm to 5 mm) and a 20 to 25 cm thick subbase of crushed stones (8 mm to 45 mm). The infiltration rate was determined to be 440 l/(s·ha) in the central region of the box to 2000 l/(s·ha) at the edges of the box. The total amount of rainwater was infiltrated through the permebale pavement during the 15 years after construction.

The total amount of heavy metals was determined using German standard DIN 38414 (1983) with aque regia. Figure 6 shows the concentrations of the heavy metals copper, zinc and cadmium in the layers of the roadbed and in the soil. The assessment of the results is done according to the German soil protection law that contains precaution values and permissible limits for soils. The quoted limits are the strict values for playgrounds.

The highest copper, zinc and cadmium concentrations were found in the pavement (paving-stones, joint filling and bedding) (see Figure 6). The permissible limits for playgrounds are not exceeded. All metal-contents were in the range of natural background concentrations of German soils (SCHEFFER und SCHACHTSCHABEL1989). No significant increase of the heavy metal concentrations in the underlying soil was observed.

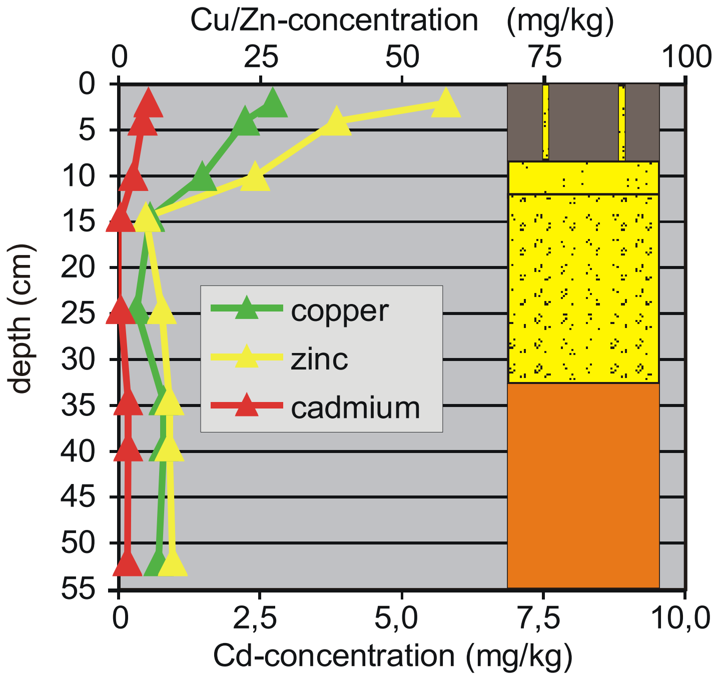

Figure 6. Concentrations of heavy metals in the pavement, the roadbed and the underlying soil

The results show that heavy metal concentrations in the upper layer of the pavement are slightly increased compared to initial contents. Permissible limits even for playgrounds are not nearly reached after 15 years of operation. The underlying soil is not affected by the heavy metals at all. These results correspond with the laboratory results (DIERKES 1999).

At the organic pollutants the mineral oil type hydrocarbons were analyzed according to DIN 38409 (1981) and the polycyclic aromatic hydrocarbons were analyzed according to DIN 38407 (1981). The results are quoted in Table 2.

At the mineral oil type hydrocarbons (spillage) an input can be seen (see Table 2). Highest concentrations were found in the joint filling. In the subbase and the soil the concentrations are also elevated. Highest concentrations with 28 mg/kg are very low. A significant increase but no endangering of the soil could be observed. PAH could not be detected at all.

In conclusion the entry of heavy metals and hydrocarbons after 15 years of operation is very low. The highest pollutant concentrations do not reach the permissible limits. In the underlying soil a slight increase of hydrocarbons was be observed, but this increase does not endanger soil and groundwater.

Table 2. concentrations of hydrocarbons in the road bed and in the underlying soil

sample	MOTH H18	PAH EPA
	[mg/kg]	
joint filling	133	< 1,5
bedding	13	< 1,5
subbase 0-5 cm	28	< 1,5
subbase 5-20 cm	15	< 1,5
soil 0-5 cm	26	< 1,5
soil 5-10 cm	20	< 1,5
soil 10-30 cm	10	< 1,5
reference value[1]	< 50	1,0
investigation value[1]	1000	20,0

[1] after Dutch guideline for soil regeneration

6 Cleaning of Permeable Pavements

Maintenance and especially cleaning is one of the most important features concerning permeable pavements. In a field study the effectiveness of a new developed cleaning device was investigated.

Figure 7. Schoolyard in Schloß Holte/Stukenbrock with porous slabs

To determine the result of the cleaning process the schoolyard of a grammar school in Schloß Holte/Stukenbrock in Germany was cleaned with the new machine (Figure 7). The pavement was constructed in 1996 and covers an area of 1500 m^2. It is made of porous concrete pavers with a filter layer. The paving stones have dimensions of 10 cm x 20 cm x 8 cm. They are bedded on a pea gravel from 2 mm to 5 mm. The joints are filled with a basalt splitt from 1 mm to 3 mm.

To determine the cleaning efficiency the infiltration capacity of the pavement was measured at three points before and after the cleaning. The measurements were carried out with a drip-infiltrometer (see Figure 8).

Figure 8. Measuring infiltration capacity with a drip-infitrometer

6.1 The cleaning machine

The new developed cleaning device works as high pressure cleaner with direct vacuum suction (see Figure 7 and 8). The vehicle has a length of 6.38 m, a width of 1.80 and a height of 2.68 m. The freshwater tank has a volume of 1,800 l, the sludge tank of 4,000 l. The power of the high-pressure-nozzles can be controlled from 150 bar to 300 bar. The suction capacity is 10,000 m^3/h at a velocity of 73 m/s. By a self-steering rear-axis the vehicle is very mobile. Besides the fixed installed cleaning module in front of the vehicle a small module for hand cleaning with an tube of 15 m is planned.

6.2 Evaluation criteria

In Germany, permeable pavements must provide an infiltration capacity of ≥ 270 l/(s·ha) (FGSV 1998), which equals a hydraulic conductivity of $2{,}7 \cdot 10^{-5}$ m/s. Due to air filled pores in the undergound a decrease of the flow velocity is expected, so that a hydraulic conductivity of $\geq 5 \cdot 4 \cdot 10^{-5}$ m/s is necessary. The worksheet A 138 of the German Wastewater Association (Planning, construction and operation of rainwater infiltration devices) takes into account regional rainfall statistics. These are normally smaller than 270 l/(s·ha), so there is a sufficient safety charge in the design.

6.3 Infiltration capacities before an after the cleaning

To assess the cleaning efficiency of the machine for the porous pavement the infiltration rate of the surface was determined before the cleaning. The measurements were carried out with the drip-infiltrometer. For all points the infiltration capacity was below 1 mm/(s·ha), so the pevement was completely clogged and could not infiltrate the rainwater sufficiently. After the cleaning procedure the measurments of the infiltration rate at the three selected points were repeated. The new infiltration capacities were very high between 1545 l/(s·ha) and 5276 l/(s·ha). All values are given in Figure 9 and are higher than the demanded 270 l/(s·ha).

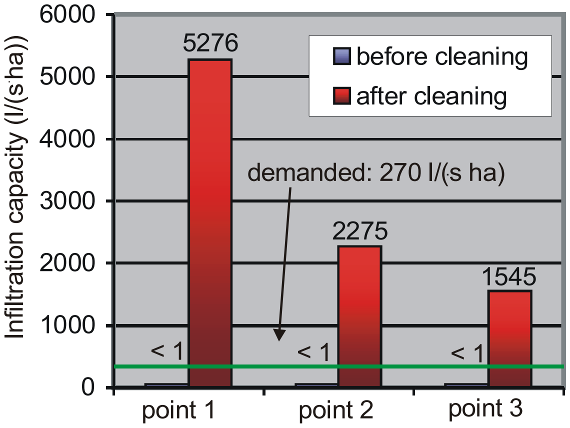

Figure 9. Comparison of the infiltration rates before and after the cleaning of the pavement

6.4 Conclusions

The determination of the infiltration capacity before and after the cleaning procedure with the recently new developed cleaning vehicle shows, that the infiltration capacity could be recovered from 1 l/(s·ha) to more than 1500 l/(s·ha). With that value, the German regulation for permeable pavements is fulfilled. A regular cleaning of the pavements is necessary.

7 Summary

Permeable pavements made of concrete paving stones are often used for stormwater-infiltration in Germany. Pollutants like heavy metals and hydrocarbons in the runoff can endanger soil and groundwater, when they are not sufficiently removed by the pavements (GOLWER 1991). Four different systems of paving stones, pavers with infiltration joints, porous concrete pavers with filter-layer, greened porous pavers and pavers with greened infiltration joints were investigated to their pollutant retention capabilities. All four systems showed very high pollution retention capacities, but the greened systems and the porous pavers work more efficient than the system with the infiltration joints. In another study, the porous concrete pavers were investigated with different roadbeds to their pollutants removal. Differences in pollution retention capacities between the subbase materials exist. The highest pollutant retention capacities were reached by crushed stones with high contents of $CaCO_3$.

To verify the laboratory results a field study on an existing pavement in front of a supermarket was carried out. The pavement consists of porous concrete blocks and was built in 1985. One parking box was dug out and samples of the pavers, the joint filling, the subbase and the underlying soil were taken and investigated for heavy metals and hydrocarbons. A slight increase of heavy metals was found in the upper 2 cm of the structure; however, the soil was not affected. Mineral oils were also found in the soil, but concentrations were very low and do not reach the permissible limits for contaminants in soils. From the results of the field study no endangering of soil and groundwater could be detected after 15 years of operation.

Clogging and the decrease of the infiltration capacity often occur in permeable pavements. A new cleaning device to recover the infiltration capacity was developed that ensures a lifetime operation of the investigated pavements. To test the new machine a clogged schoolyard was cleaned. Infiltration capacities were recovered from less than 1 l/(s·ha) before the cleaning up to values larger than 1500 l/(s·ha) after the cleaning. The new machine seems to be a suitable device for the maintenance of porous pavers.

The use of permeable pavements is a sustainable method, if planning, construction and maintenance are carried out according to the latest research results.

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