Pollution retention of different permeable pavements with reservoir structure at high hydraulic loads

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ABSTRACT
Permeable pavements for sustainable stormwater management and source control have been furthered and investigated in Germany for many years. In particular the runoff from streets and parking areas with low traffic densities can be permitted to infiltrate with the aid of concrete pavers with wide joints. But runoff from traffic areas contains pollutants such as heavy metals and hydrocarbons that can endanger the soil and groundwater. Furthermore solids in stormwater runoff bring about clogging. Since clogging is a well known problem, it is not clear how long permeable pavements provide sufficient infiltration capacity and which factors must be considered at planning and construction if a long service life of the systems is to be ensured. Investigations on the hydraulic behaviour and the pollutant transport were carried out on a car park of a sports facility. Parts of the traditional pavement of the car park were reconstructed with trenches covered with permeable pavers. The ratio of impermeable to permeable area is 16:1. The infiltration capacities of the pavers after three years of operation and the water quality along the path from rainwater and runoff to seepage water and groundwater were observed. Additional laboratory rigs were charged with an artificial runoff to determine the pollution retention capacities of different substrates. It is concluded that the system is not satisfactory in respect of its hydraulic behaviour but that it works very efficiently in respect of pollution retention.

KEYWORDS
Stormwater infiltration; permeable pavers; heavy metals; pollution control

INTRODUCTION AND PROBLEM IDENTIFICATION
Permeable pavements with reservoir structure for sustainable stormwater management and source control in urban areas are extensively furthered and investigated in Germany. Runoff from streets and car parks is allowed to infiltrate to support groundwater recharge and to reduce hydraulic stress in sewer systems and receiving waters. An additional drainage system is not always necessary, so the measures are generally more cost effective than traditional drainage systems. But runoff from traffic areas contains pollutants which can endanger soil and groundwater in the long run (Van Dam et al. 1986, Hütter et al. 1998). Furthermore it is well known that particles in runoff provoke clogging, so that surfaces must be maintained to regenerate infiltration capacities from time to time. Although clogging is known to be a significant problem, it is not yet clear how long permeable pavements are able to provide sufficient infiltration capacity. Recommendations for the planning and construction of such pavements, which will ensure high pollutant retention and sufficient permeability, are required (Dierkes et al. 2002).

STUDY OBJECTIVES

The objective of the presented study is to evaluate the hydraulic and qualitative performance of a permeable pavement, that was built on an existing car park of a sports centre. To disconnect the impermeable area from the drainage system, the traditional pavers were removed in stripes of about 1 m, and trenches to store the runoff were built (see Figure 1 and 2) . These trenches were covered by a permeable pavement with wide joints, where the water can infiltrate into the trench. The other part of the area remained sealed (see Figure 1).
The facility is investigated over a period of two years. Different joint fills were used, to identity the effects of the material and to get information about the velocity of clogging, the spatial distribution of clogging and to find measures to regenerate the pavers. Three different trench substrates were used, to see the pollution retention capacities of different materials.
The aim of the study is to find recommendations for the design, the construction and the maintenance of permeable pavers under high loads of runoff and pollutants. Materials should be identified, that give highest security for soil and groundwater, and that make sense from the economical point of view.

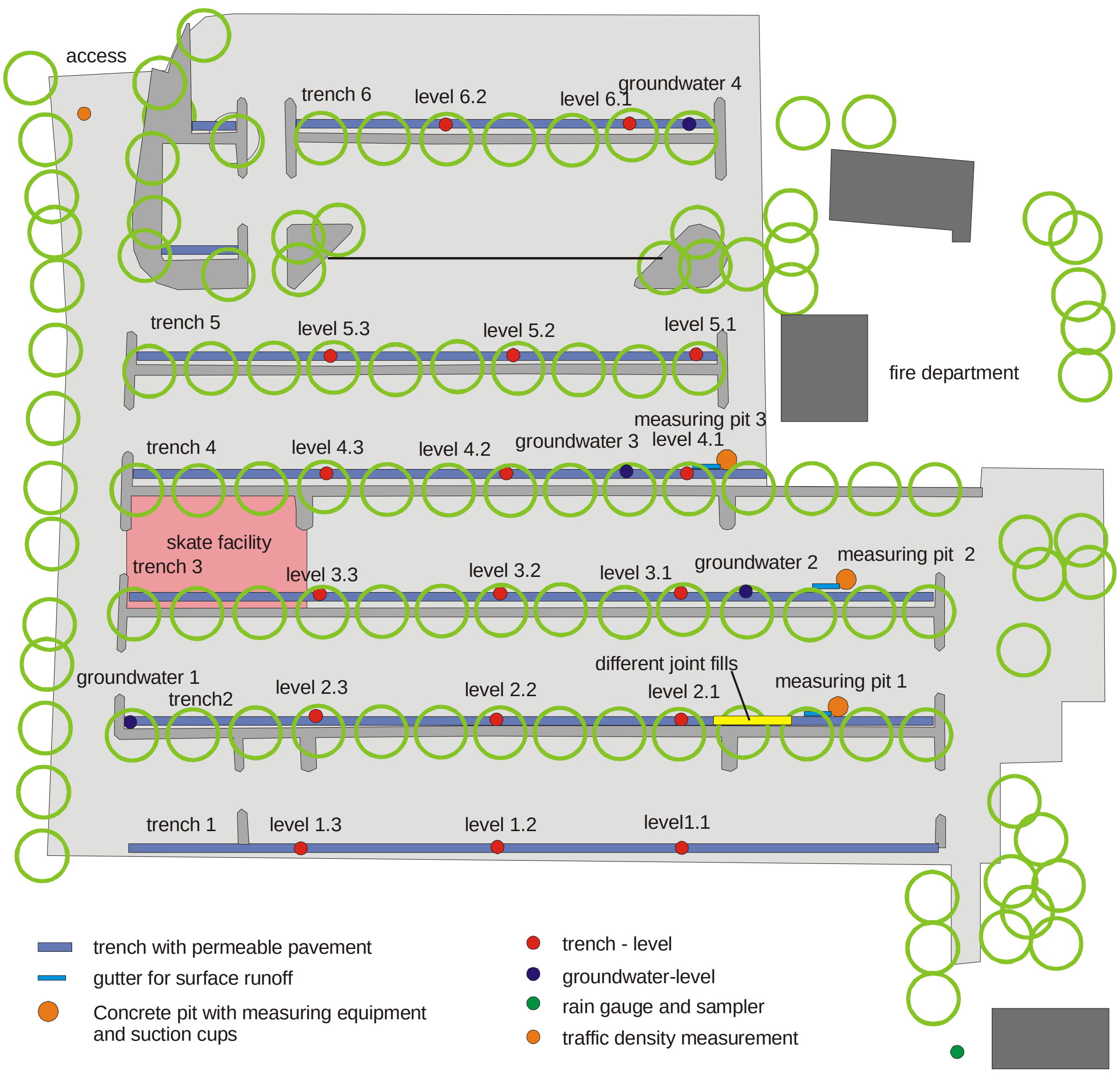

Figure 1. Parking area with sampling and observation points

METHODOLOGY

The car park was disconnected from the public sewer system in 2001. Runoff from the parking areas is collected and allowed to infiltrate into six trenches (see Figure 1). The measurements were started in 2003 two years after the reconstruction measures. The complete path of water and pollutants from their presence in stormwater to their arrival in groundwater is sampled.

A rain gauge was installed to get information about the inflow to the infiltration system (see Figure 1). A rain sampler was fixed besides the gauge. Rainwater is collected via a glass funnel and is collected in a brown glass bottle.

Surface runoff from the car park is collected via three surface drains, each three metres long. These are situated besides the trenches 2, 3 and 4. The runoff is directed through a pipe into a concrete pit, where the samples are taken. The whole amount of water is collected in 200 L sampling vessels. Samples were taken after the water in the tanks was stirred up. 34 sampling wells were distributed in the trenches (see Figure 1). Here the water level can be measured in addition. Suction cups are placed in the soil beneath the trenches, positioned 10, 20 and 30 cm under the trench. Each horizon consists of three cups to get representative water samples. Additionally four groundwater wells were drilled to determine the water level and to take samples from groundwater. With this concept, the whole pathway of water from the atmosphere to the groundwater can be observed. A device to measure the traffic density on the car park was installed.

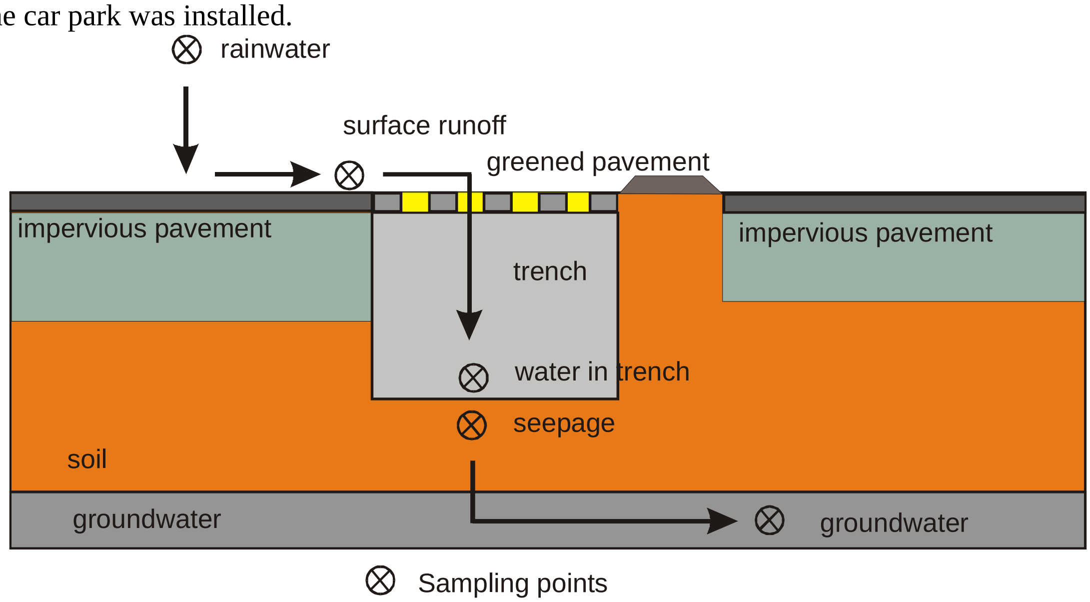

Figure 2. Cross-section of the measurement site with sampling points

Measurement of infiltration capacity

A drip infiltrometer for the determination of the infiltration capacity of paved surfaces was used for permeable pavement according to the German regulations. For this a metal ring of 3 cm in height (d = 54 cm) is set on a test area and is sealed by mortar against the surface. The ring marks the inner test area and prevents water flowing out of this area. By a sprinkler device the test area and the area outside the ring is rained during the test period. By irrigating the outer section of the ring, the water inside the test area is forced to infiltrate vertically and not laterally at the ring boundary. To simulate realistic rain conditions, the sprinkler system is designed in such a way that a water film with a thickness of just a few millimetres is created, so no unrealistically high water pressure is realized as is the case with other infiltration tests. The idea of the test is to irrigate the test area at an intensity at which no surface runoff is created. The maximum infiltration capacity of the surface is determined as a function of time.

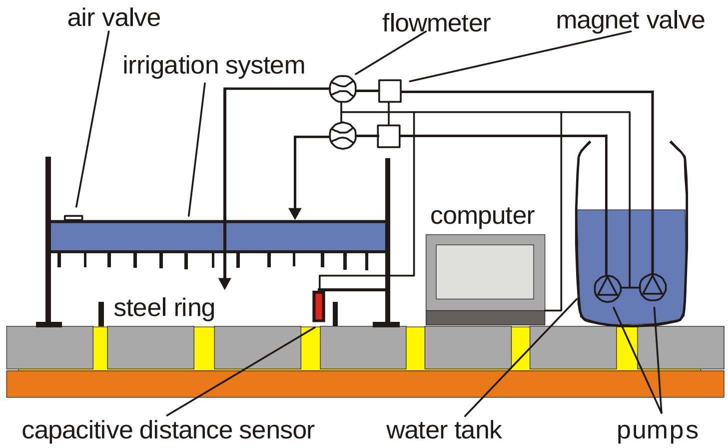

Figure 3. Schematic illustration of the infiltrometer

The sprinkler facility consists of a plexiglass trough with injection needles creating raindrops. The original measuring device gave a maximum rain intensity of about 144 mm/h. For this investigation the density of the needles was increased with 625 needles distributed over an area of 80 cm x 80 cm. The inflow of water into the sprinkler is measured by a flow meter and is recorded by a computer. Because the water film in the test area remains constant, the infiltration capacity equals the simulated rain intensity. The water film is controlled by a capacitive distance sensor. The height of water varies in the contact hysteresis of the sensor (about 0.1 mm). The sensor controls a pump feeding water to the sprinkler. When the height of the water films sinks below a certain level, the pump is started and is stopped again when the water exceeds a certain level.

Laboratory rigs

In an additional laboratory study the trenches were duplicated in test rigs with dimensions of 0.40m x 0.40 m x 0.80 m. The test rigs are filled in an identical manner to the car park pavement as can be seen in Table 1. Five different joint fills were investigated in terms of their pollutant retention capability and clogging sensitivity. The different substrates used can be seen in Table 1. The trench material used for the first test series was a crushed limestone with a grain size distribution from 0 mm to 45 mm. This is the material typically used in Germany.

Table 1. Configuration of the test rigs with permeable pavements and trenches

	1	2	3	4	5
joint fill	split 2/5 mm	recycled concrete	split 1/3 mm	blend E	volcanic material
trench material	0 / 45 mm	0 / 45 mm	0 / 45 mm	0 / 45 mm	0 / 45 mm
picture					

An artificial traffic runoff, that was mixed in a 1000 l tank, was sprinkled on to the rigs. The runoff was spiked with lead, copper, zinc and cadmium. Up to the present time 18 years of operation have been simulated.

RESULTS

Firstly the hydraulic performance of the system is presented. The second chapter contains the behaviour in respect of pH and heavy metals as found in the field study. Laboratory tests and a short outlook follow.

Hydraulic performance of the system

When the trenches were constructed, the joints were filled with a 2/5 mm limestone split (grain size distribution 2 - 5 mm). After the system had been in operation for three years, the infiltration rates were measured at five different points on the car park on two occasions. The results are given in Table 2.

The first two lines show the infiltration rates after a measuring period of ten minutes, the last two lines show the final infiltration rate after at least one hour of measurement. The rates range from 7.5 mm/h to 395.4 mm/h. The German guidelines for the construction of permeable pavements require an infiltration capacity of at least 97.2 mm/h. On the investigated car park the ratio between the classic, impermeable pavement and the permeable pavement is 16:1, so the infiltration capacity must be 16 times higher than the afore-mentioned figure. This means that a calculated infiltration rate of about 1555 mm/h must be achieved for the permeable pavement. As one can see, this value was not reached. This leads to the conclusion that a significant part of runoff is drained away by the additional surface drainage system. No real trend can be seen between the measurements for September and January. The infiltration rates at positions 5 and 6 were significantly higher. The reason for this is not known at present. Further measurements will follow.

Table 2. Infiltration capacities in mm/h

	trench 2	trench 4	trench 5	trench 6	trench 6a
September 04, 10 minutes	18.3	110.2	102.6	66.2	40.7
January 05, 10 minutes	11.4	111.9	395.4	130.0	54.8
September 04, final rate	7.5	46.8	59.4	48.6	32.4
January 05, final rate	5.5	47.1	215.6	113.2	31.2

The second conclusion is that the 2/5 mm split used was not suitable for this area of application, because of its low hydraulic conductiviy. Accordingly five different materials were tested for their behaviour during a second investigation period. The results obtained with these materials after six months of operation are shown in Figure 4. The 2/5 split gave the lowest infiltration rates. These are above the requirements, but seem to decrease very fast (see Figure 4 (3800 mm/h after six month of operation) and Table 2 (< 400 mm/h after three years of operation)). A higher infiltration capacity of about 5000 mm/h was found for a 1/3 split. The reason for this could be the steeper grain size distribution curve of the latter.

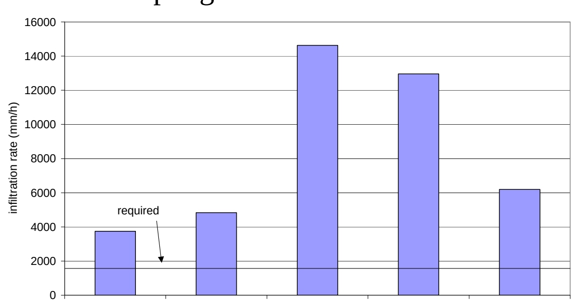

Figure 4. Infiltration capacities for different joint fills six months after construction

The pores of this split are better able to provide a high infiltration capacity. The highest values were found for a 2/5 mm crushed concrete and a crushed volcanic material. It is possible that these substrates clog up more slowly than the 2/5 mm split.

Results of the field investigation

The results of the first year of measurements (pH and heavy metals) are given in Table 2. Displayed are minimum, maximum and mean values. The pH in the rain is between 5.4 and 9.0 with a mean of 7.3. In the runoff the mean is 0.3 points higher, that of the seepage water 7.3. The pH in the groundwater is higher at 8.7 as a result of high $CaCO_3$ concentrations in the aquifer.

The lead and cadmium concentrations are low. Cadmium could not be detected in any of the samples. The mean concentrations for lead are 8 μg/L. The concentrations in the groundwater are higher whereby this is not a result of the stormwater infiltration. There may be an influx from another source in the area, connected perhaps with the former use of the car park.

Table 3. pH and heavy metals in rainwater, surface runoff, seepage water and groundwater

		pH	lead	cadmium	copper	zinc
rain	mean	7.3	8	< 2	14	65
	min	5.4	5	< 2	5	30
	max	9.0	20	< 2	40	140
surface runoff	mean	7.6	8	< 2	43	130
	min	6.2	5	< 2	5	10
	max	8.3	30	< 2	550	1200
seepage	mean	7.3	8	< 2	15	138
	min	6.8	5	< 2	5	40
	max	7.7	20	< 2	100	290
groundwater	mean	8.7	28	< 2	19	62
	min	6.4	5	< 2	5	10
	max	13.3	210	< 2	110	190

14 μg/L copper were found in the rainwater. The concentrations increase in the surface runoff to a mean value of 43 μg/L. The maximum concentration found was 550 μg/L. 86 μg/L is the level normally found on car parks of supermarkets with higher traffic densities in Germany (Coldewey et al. 2004). The low concentrations found in this study may be a result of the low traffic density on the car park (350 vehicles/day). The seepage water contains about 15 μg/L. This shows that the trenches are trapping copper so that the concentrations in the seepage are as low as in the rainwater. Groundwater concentrations are higher but are below the German permissible limit for seepage water of 50 μg/L.

An average of 65 μg/L zinc was found in rain. The concentrations increase to 130 μg/L in the surface runoff. These concentrations are low compared to other studies (Coldewey et al. 2004). The level in the seepage water was 138 μg/L. This shows the high mobility of zinc in the trench. In groundwater 62 μg/L were found, which is only about 10 % of the 500 μg/L permitted by the German guidelines. Accordingly the zinc concentrations do not appear to be a problem at all at this car park.

The pathway of the main metals, namely copper and zinc, from rain to groundwater can be seen in Figure 5. Concentrations increase from rainwater to surface runoff. The levels of the metals are low compared to car parks with higher traffic densities. A decrease of the values can be observed in the seepage water and groundwater, which is an effect of the pollution retention capacities of the pavement and trenches.

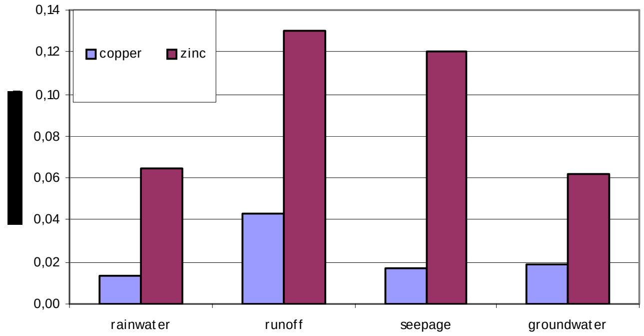

Figure 5. Mean copper and zinc concentrations in water samples

Results of the laboratory rigs

The field investigations show the pollutant concentrations after three years of operation, but a real system has to work for at least 25 years without endangering soil and groundwater. To predict the future behaviour in respect of the pollutants, laboratory rigs were charged with an artificially formulated runoff to obtain results in a shorter time. This was sprinkled intermittently on to the test rigs to simulate natural rain events. The five different joint fills from the field investigations were again used. The simulations were done with a rain intensity of 8 mm/h. The concentrations in the artificial road runoff were increased by a factor of 10 relative to the actual road runoff concentrations to reduce the amount of water that had to be passed through the rigs. The concentrations of metals used in the artificial runoff were 3.6 μg/L cadmium, 1,600 μg/L zinc, 240 μg/L copper and 138 μg/L lead. In total 39 rain events with loads representing 1.7 years of operation were simulated. Since the concentrations in the effluent did not show any significant increase, the concentrations in the artificial runoff were increased by a further factor of ten in order to attempt to get a breakthrough of the metals. Another 39 rain events were simulated with loads representing in total 18 years of operation being passed through the columns. The efficiencies of the heavy metal retention can be seen in Table 3.

Table 3. Heavy metal retention levels of the test rigs after the simulated 18 years loading

	rig 1 (%)	rig 2 (%)	rig 3 (%)	rig 4 (%)	rig 5 (%)
Zn	96.3	94.2	96.3	96.8	95.2
Cu	98.0	98.0	99.3	98.0	98.0
Pb	99.8	99.8	99.8	99.8	99.8
Cd	99.9	99.9	99.9	99.9	99.9

A significant increase of the zinc- and copper concentrations could be noticed during the last rain events, but the retention efficiency remained high. The overall efficiency is more than 99 % for lead and cadmium, more than 98 % for copper and between 94 % and 96 % for zinc. Differences between the different joint fills were insignificant at the beginning of the tests, but became more important at the end of the measurements. The highest pollution retention capacities were found for the recycled blend material and the recycled concrete. The classic joint fill shows the lowest pollution retention capacities and seems in addition to have the lowest infiltration rates of all the materials tested.

Outlook

Parallel to the laboratory tests, adsorption isotherms of all material were determined according to the OECD guideline (OECD 1981). With these values a finite element model will be calibrated which will aid predicting pollutant transport in the future. Regular measurements of the infiltration rates will show which substrates tend to clog and which are suitable for a long term use.

CONCLUSIONS

The field investigations on the car park show clearly that the permeable pavement is not able to pass the total amount of runoff. The infiltration rates of the permeable section of the pavement are too low to permit the heaviest rain events to be discharged. The car park could only be disconnected from the wastewater sewer with the aid of a secondary drainage system with an open channel and a large infiltration basin. The ratio of 16:1 between impermeable and permeable surface is too high according to the findings of this investigation. The ratio should be not higher than 4:1. With a suitable joint fill ratios of 6:1 up to 8:1 seem to be theoretically possible, but it will not be possible to draw conclusions on this until investigations have been continued for a further year.

The pollutant concentrations of heavy metals seem to be low on the car park, possibly because of the low traffic density. The mean concentrations found do not exceed the German permissible limits. However differences between the different joint fills can be seen. Not all substrates are able to provide high pollution retention. As a recommendation, materials with high $CaCO_3$ concentrations and an organic component seem to offer the best solution due to their ability to cause precipitation of heavy metals and their high adsorption capacities for all pollutants. The 1/3 or 2/5 mm split as traditionally used is not suitable and should be replaced. Long-term studies and the predictions on pollutant transport underground will provide further information. The main conclusion of the study is that stricter regulations are necessary on the design of permeable pavements, especially where the impermeable area / permeable area ratio is greater than 2:1. Compromises must be made between groundwater protection and sensitivity to clogging.

ACKNOWLEDGEMENT

The study presented was sponsored by the Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen (MUNLV) and the Emschergenossenschaft.

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