Effective pollutant retention capacity of permeable pavements for infiltrated road runoffs determined by laboratory tests

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Abstract The infiltration of urban runoff always implies an entrance of pollutants into the soil and ground water. Due to legal regulations in many communes there is no longer any permission needed for stormwater infiltration, if administrative regulations and the requirements of standards are observed. The results of a research project carried out under the heading “Development of an assessment procedure for permeable pavements” show, that the pollutant retention capacity of permeable pavements varies considerably, depending on the material and the specific reactive surface. The objective of the study was to work out recommendations of suitable permeable pavements for different types of urban runoff. Selected data about the quality of urban runoff was compiled into a runoff matrix, which was used for defining characteristic dilutions. In batch tests, the material of the infiltration devices is penetrated with the dilutions. A test installation in large scale is used to calibrate the sorption coefficients derived from the batch experiment.

Keywords Large scale tests; permeable pavements; road runoff; sorption tests; stormwater infiltration

Introduction

As a result of a forward-looking sustainable water policy in North Rhine-Westphalia, policies for the local disposal of stormwater runoff have been clearly established. Since 1996, legal regulation in North Rhine-Westphalia stipulates that any stormwater arising on newly built real estate has to be infiltrated, used for irrigation or discharged locally into receiving water. By taking advantage of the soil’s retention capabilities runoff peaks can be reduced by temporary storing the stormwater, so that development areas can be connected to existing sewers and treatment plants with limited capacity. North Rhine-Westphalia and especially the Emscher catchment area (865 km²), is characterized by its considerable population density (2.3 million inhabitants) and its high degree of sealed areas. The average proportion of urban and traffic areas in North Rhine-Westphalia is about 12.2% and 6.7% of the total area (Federal Statistic Office, 2002). At the congress “Rain on Correct Ways”, which was held by the “Emschergenossenschaft” in the Spring of 2003, the objective was set to disconnect 15% of the sealed areas from combined sewers in the Emscher region in the next 15 years (Stemplewski, 2003).

In order to achieve this ambitious goal, it is necessary to infiltrate not only roof runoff, as is often done with the use of swales and trenches, but also road runoff. Raasch and Becker (2001) explained the possibilities and limitations for a sustainable rainwater management in the Emscher region. The most important restrictive criterion for the feasibility of infiltration facilities, is the availability of free space. Due to the high concentration of structures, there is not enough space for infiltration facilities such as basins or swales. Another restrictive criterion is the minimal distance between the groundwater and the surface, which means that infiltration facilities with a smaller footprint on the land, like trenches and sinks cannot be set up. An alternative being currently researched, is the use of permeable pavements made of...
concrete blocks with infiltration pores or porous asphalt for areas without or with only low traffic like in parking lots, residential roads or driveways.

Because of the potential hazard of traffic-generated pollution in groundwater, particularly from heavy metals, polycyclic aromatic hydrocarbons and mineral oil type hydrocarbons, the infiltration of road runoff has to be regarded critically. Since heavy metals are not degradable, they constitute an important source of soil contaminants. The significantly heavy metal loads in road runoffs, originate mainly from exhaust fumes and the abrasion caused by tires and steel parts. In order to carry out a risk assessment of soil and groundwater pollution caused by the infiltration of road runoff, it is necessary to be aware of the pollutant transport in the pavement and the roadbed. For a better understanding of the transport and sorption processes in roadside soils, Marcos et al. (2001) examined the mobility of zinc and lead in column experiments with Fontainebleau sand. Exchange reactions between lead, zinc and calcium could be observed and simulated with an impact model. Although the main reactions identified are valid for unsaturated conditions, further investigations with porous media under more realistic conditions are required (Marcos et al., 2001). Research carried out by Newman et al. (2001) looked at the bio-degradation of clean motor oil by different prepared laboratory rigs. The results showed, that the microbial populations within the permeable pavement are robust and resistant against the highly variable road runoff. Rommel et al. (2001) examined the infiltration capability of permeable pavements. The clogging reduced the effective permeability to 80% of the new product value, which depends on the nature and rate of sediment supply. However, further research needs to be carried out in order to finally answer the question of the pollutant transport and thus the hazard potential emitted from permeable pavements. The procedure described here attempts to answer these questions.

Methodology

To predict the pollutant transfer in permeable pavements caused by the infiltration of road runoffs, a three-tier approach was chosen. Arriving at the sorption isotherms for different road construction materials was done by batch tests performed with a horizontal shaker in the laboratory. From these laboratory tests, sorption coefficients were derived and were used in a model to simulate the large-scale tests, which is not subject of this report. The investigations on the test facility in large scale were carried out in order to calibrate the sorption coefficient derived from the batch tests. The same dilutions were used for the large scale and the laboratory tests. The concentration ratios of the spiked heavy metals were based on the middle runoff concentrations of predefined runoff-forming surfaces in urban areas. Therefore, as a first step, theoretical data about runoff concentrations from research projects were collected in a so-called runoff matrix and this data was evaluated with respect to trustworthiness and transferability. The permeable pavements investigated, along with their substructure, are shown in Figure 1.
The chemical parameters of the runoff matrix (see Table 1) can be evaluated as follows.

- It can be noticed that cadmium concentrations have been reduced in the last few years and do not reach the critical value of the German Drinking Water Ordinance, but due to its toxicity and its mobility cadmium is still important.
- Zinc and copper are primary components of roof runoffs, which originate from structural parts of roof materials. The inspection values of the German Federal Soil Protection Ordinance are exceeded.
- Lead appears in varies runoffs, but as a result of a declining use of leaded fuels its concentration in road runoffs has a decreasing tendency.
- Calcium sulfate is caused by dry deposition of roofs and is the dominating anion.
- The use of de-icing salts lead to raised sodium chloride concentrations in road runoffs. When composing the dilutions it had to be considered that ion competition effects could take place comprehensively. In addition, chemical aspects like the poor solubility of lead sulfate had to be taken into account.

**Laboratory tests for determining sorption isotherms**

Firstly, the material had to be prepared for the laboratory tests. Therefore the concrete blocks were broken up with a jaw crusher before being sieved through a mesh opening of 2 mm. This latter procedure was also valid for the roadbed and the base layer material. The graded material was put into a drying oven at 105°C until weight constancy was reached. Of the total volume, 9.6 g were weighed into a 250 mL bottle, to which 240 mL dilution volumes were added, so that the relation of water and solid amounts to 25 L/g.

Table 1 presents the configuration of the dilutions used and the heavy metal concentration content. The dispersion was gently shaken at 260 rpm for one week, so that all the particles could come into contact with the dilution. After one week, the batch test could be stopped, because it could be assumed, that equilibrium was reached. For the analysis, 40 mL samples were taken from the dilution, which were centrifuged with 4000 rpm for the separation of the suspended matters. The acid stabilized samples were analyzed by using an inductively coupled plasma atom emission spectrometry (ICP-AES). All tests were conducted twice, in order to be able to detect failures in the performance and or the analysis. If the analysis results of two samples deviated too much from each other, the test series was repeated.

**Large-scale tests for determining pollutant retention capability**

The test installation consisted of five main parts, two removable irrigation units, two exchangeable lysimeters for the permeable pavement and a base structure with the
measurement equipment as shown in Figure 2. The irrigation unit consisted of a closed acrylic glass tank with 576 hypodermic needles in the floor panel to simulate realistic rainfall. The acrylic glass tank was supplied with a flexible tube pump, which was connected to a reservoir. The intensity of the rainfall was measured by an inductive flow meter in the supply, which controlled the outflow of the flexible tube pump.

The pavement, the roadbed and the base layer were installed into the lysimeter in full size and were irrigated with synthetic runoff. The seepage water was discharged into the proper hopper and possible surface runoff was discharged into a gutter attached to the outside of the lysimeter. From the hopper the collected seepage water was pipelined to the sampling site. Four pipes were equipped with pH meters, which measured the pH value of the seepage water continuously. During the sprinkler irrigation, samples were taken from the seepage water, which were determined to certain chemical parameters listed in Table 1.

Each lysimeter was subdivided into four boxes with an area of 0.50 m × 0.50 m. The boxes on which the screen was arranged differ in altitude. Two boxes contained the complete road structure with pavement, roadbed and base layer. In the third box, there is only the pavement with the roadbed and in the fourth, only the pavement. Therefore, it was possible to determine the pollutant retention capability of each individual layer. The lower layer was constructed on an integrated screen in order to prevent grains of small diameters entering the drain. The thickness of the compacted base layer was 0.40 m, that of the roadbed was 0.04 m. The side panels of the lysimeter had metal eyehooks attached to them, in order to transport the lysimeter with the test material by crane.

In order to determine the initial concentration of material from which the pollutants are washed out, the pavement was sprinkled with normal tap water from Friday evening to Monday morning. At the end of this sprinkling irrigation process with an intensity of 20 L/(s · ha), a sample was taken. This process also guaranteed an identical moisture penetration of the road material. Afterwards, the irrigation unit was emptied and the synthetic runoff containing the heavy metals was prepared. The reagents, such as cadmium, copper, lead and zinc were added to the dematerialized water and stirred thoroughly for a minimum of 5 minutes to ensure complete mixing. Tests conducted in advance with pavement and bedding layer had shown a high pollutant retention capacity of up to 96.8% for copper and up to 93.3% for zinc (Fach et al., 2002). The synthetic runoff had a concentration of 1 mg/L of each heavy metal. Field tests over an operation time of four years with a permeable pavement, which had a joint ratio of 30% confirm the laboratory test results (Nadler and Meissner, 2004). In order to reduce failures due to seepage concentrations in the range of the detection limit of the ICP-AES used, the technical tests were carried out with the concentration grades numbered II and IV. Unlike the sprinkling volume the heavy metal load did not correspond directly to a specific time interval, e.g. one year.
The pH value of the heavy metal containing water in the reservoir was adjusted to 4.1 in order to take into account the aging of the carbonate containing building materials. Additionally, the acid prevented the dissolved heavy metals from precipitating out of dilution. To ensure correct concentrations, a sample was taken from the prepared water and analyzed on the added heavy metals using the ICP-AES.

The pavement was sprinkled with the synthetic runoff for 5,775 minutes. During the testing time, sprinkler irrigation phases and drying phases alternated once per hour. The sprinkling intensity was about 46.5 L/(s · ha) so that the amount of synthetic rain complies with the mean annual height of precipitation of the Emscher region. Samples were taken according to a specified time schedule. The samples were analyzed based on the parameters listed in Table 1. The retention capacity of the pavement was determined by the difference between the heavy metal concentrations in the synthetic runoff and the seepage water.

**Test results and discussion**

As a result of the multitude of evaluated tests the presentation is limited to selected examples, with which the results are exemplary described. On basis of these examples it is possible to reproduce the determination of the pollutant retention capability of permeable pavements.

**Sorption isotherms describing the pollutant transport in the road construction**

To simplify matters the presented results in detail are limited on two materials, the joint material and the base layer material. For all road construction materials sorption isotherms were determined by using a parameter-fitting program. In a first step the five measurement results of both test series were weighted with respect to their variation. In a second step the isotherms coefficients were imported into Excel, which was used to optimize the sorption isotherms graphically. Due to the ascending curve progression of the examined materials, only the Langmuir isotherm was suitable, for the idealistic description of the materials sorption performance. The functional correlation of sorbed mass and concentration of the equilibrium solution could be described according to Langmuir as (Sparks, 1995):

\[
c_{\text{ sorbed }} = \frac{k_1 \cdot c_{\text{dissolved}}}{1 + k_2 \cdot c_{\text{dissolved}}}.
\]

The sorption isotherms obtained are represented in Figure 3. As expected the limestone gravel showed a better sorption performance due to the higher lime content than the crushed basalt. The lime content is important for the pH value of the dispersion, which specifies precipitation processes of heavy metals. This is also recognizable when comparing the parameter \(k_1\) and \(k_2\), which are for the crushed basalt 4,160 and 2,828 and for the limestone gravel 16,088 and 4,254. The lines marked A1 and A4 represent the middle runoff concentrations of the runoff-effective areas from the collected literature data, which is represented by the dilution No. 1. The line marked A1 in the diagram represents mean runoff concentrations of unsealed areas, like grassland or gardens. The runoff of green roofs and of

![Figure 3](https://iwaponline.com/wst/article-pdf/51/2/37/434781/37.pdf)

Figure 3 Sorption isotherm of the base layer material (left side) and of the joint material (right side)
<table>
<thead>
<tr>
<th>dilution/element</th>
<th>concrete blocks with voids</th>
<th>concrete blocks with joints</th>
<th>porous concrete blocks</th>
<th>crushed basalt 1–3 mm</th>
<th>crushed basalt 2–5 mm</th>
<th>brick substrate 2–5 mm</th>
<th>Limestone gravel 0–45 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_1$</td>
<td>$k_2$</td>
<td>$k_1$</td>
<td>$k_2$</td>
<td>$k_1$</td>
<td>$k_2$</td>
<td>$k_1$</td>
</tr>
<tr>
<td>L1 Zn</td>
<td>5055.3</td>
<td>0.1797</td>
<td>4298.7</td>
<td>0.9983</td>
<td>3893.8</td>
<td>0.3939</td>
<td>4160.2</td>
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<tr>
<td>L2 Cu</td>
<td>10,774</td>
<td>4.7547</td>
<td>19,818</td>
<td>5.833</td>
<td>8631.4</td>
<td>4.1841</td>
<td>4073.6</td>
</tr>
<tr>
<td>L2 Pb</td>
<td>2583.7</td>
<td>1.2163</td>
<td>3698.3</td>
<td>2.2034</td>
<td>1504.9</td>
<td>0.9017</td>
<td>507.03</td>
</tr>
<tr>
<td>L3 Zn</td>
<td>14,127</td>
<td>3.6144</td>
<td>27,881</td>
<td>5.9938</td>
<td>5386.7</td>
<td>1.6611</td>
<td>3611.1</td>
</tr>
<tr>
<td>L3 Cu</td>
<td>2614.6</td>
<td>4.3736</td>
<td>1341.5</td>
<td>1.9109</td>
<td>3030.1</td>
<td>3.475</td>
<td>4097.6</td>
</tr>
<tr>
<td>L4 Zn</td>
<td>999.6</td>
<td>1.3544</td>
<td>9262.3</td>
<td>0.01</td>
<td>5973.8</td>
<td>0.4015</td>
<td>2488.2</td>
</tr>
<tr>
<td>L4 Cu</td>
<td>3040.4</td>
<td>0.2860</td>
<td>17,389</td>
<td>3.2056</td>
<td>12,879</td>
<td>0.0001</td>
<td>2344.5</td>
</tr>
<tr>
<td>L5 Zn</td>
<td>5996.8</td>
<td>0.2043</td>
<td>14,272</td>
<td>2.9575</td>
<td>5973.8</td>
<td>0.4015</td>
<td>598.34</td>
</tr>
<tr>
<td>L5 Pb</td>
<td>2029.2</td>
<td>0.3092</td>
<td>2523.5</td>
<td>0.8751</td>
<td>12,879</td>
<td>0.0001</td>
<td>2344.5</td>
</tr>
</tbody>
</table>
roofs without metal parts is denoted A4. In Table 2 the isotherm coefficients derived of all tested materials and dilutions are summarized. Some of the values may change due to outstanding retries of batch tests.

### Pollutant retention capability of permeable pavements

The illustrated results come from the large-scale tests with concentration-grade II. Since the used material was different and the functionality was alike, pavement No. 1 (Figure 1, left) and pavement No. 2 (Figure 1, third from left) could be compared in respect to seepage water concentrations. Obviously, the brick substrate sorbed heavy metals better than the crushed basalt, which were used for the joints and the roadbed. Due to the organic components included in the substrate the solved heavy metal formed complexes, so that seepage water concentrations were reduced. Hence the pollutant retention efficiency of pavement No. 1 (Figure 4, right) was 85.3%, that of pavement No. 2 (Figure 4, left) was 95.6%. If the entire road constructions including roadbed and base layer are compared, the pollutant retention efficiency of both options is equivalent. The road construction with the brick-filled infiltration pores had a pollutant retention efficiency of 99.2%, that with the basalt filled infiltration pores had 99.0%. The breakout curves were typical in respect that seepage water concentrations of pavement with roadbed ascended to the end of the test duration. Whereas seepage water concentrations of pavement without substructure were elevated from the beginning of the test.

Table 3 contains the calculated pollutant retention capacities that were obtained from the effluent graphs after sprinkling with synthetic runoff of concentration-grade II. Initially it is remarkable that the pollutant retention capacities are generally of high quality, although the heavy metal load in the test was a multiple of that under natural conditions. Nevertheless the different road constructions differ from each other with regard to the pollutant retention capacity. The porous concrete block paving adsorbs most of the pollutants, followed by the concrete block paving with substrate infill. The concrete block pavings with joints perform inferior than the other two systems.

### Conclusion

Before the research project was performed the pollutant retention efficiency of different pavements was assessed globally. Particularly, the research project “Development of an assessment procedure for permeable pavements” and the presented methodology showed that a material-specific evaluation of the pollutant retention capability is possible. In a next step the achieved data will be used in a model to simulate long-term effects of road runoff infiltration. Therewith it will be possible to estimate infiltration facilities in respect to the hazard potential, in order to take measure, which close to nature rainwater management is appropriate and prevents soil and groundwater contamination.

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**Figure 4** Relative seepage water concentrations during the test period

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Table 3 Pollutant retention capacities as percentage

<table>
<thead>
<tr>
<th>dilution/element</th>
<th>concrete block paving with substrate infill</th>
<th>concrete block paving with narrow infiltration pores</th>
<th>concrete block paving with wide infiltration pores</th>
<th>porous concrete block paving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-R-B</td>
<td>P-R</td>
<td>P</td>
<td>P-R-B</td>
</tr>
<tr>
<td>L1 Zn</td>
<td>99.2</td>
<td>98.5</td>
<td>95.6</td>
<td>98.9</td>
</tr>
<tr>
<td>L2 Cu</td>
<td>99.8</td>
<td>99.2</td>
<td>96.3</td>
<td>99.5</td>
</tr>
<tr>
<td>L2 Pb</td>
<td>99.6</td>
<td>99.3</td>
<td>94.9</td>
<td>99.2</td>
</tr>
<tr>
<td>L3 Zn</td>
<td>98.9</td>
<td>98.7</td>
<td>93.7</td>
<td>97.3</td>
</tr>
<tr>
<td>L3 Cu</td>
<td>99.6</td>
<td>99.3</td>
<td>88.1</td>
<td>97.6</td>
</tr>
<tr>
<td>L4 Zn</td>
<td>98.8</td>
<td>96.9</td>
<td>92.7</td>
<td>96.7</td>
</tr>
<tr>
<td>L4 Cu</td>
<td>96.9</td>
<td>96.7</td>
<td>92.7</td>
<td>96.7</td>
</tr>
<tr>
<td>L5 Zn</td>
<td>99.7</td>
<td>96.0</td>
<td>89.2</td>
<td>99.0</td>
</tr>
<tr>
<td>L5 Pb</td>
<td>99.8</td>
<td>99.5</td>
<td>93.3</td>
<td>99.6</td>
</tr>
</tbody>
</table>

P: pavement only
P-R: pavement with roadbed
P-R-B: pavement with substructure (roadbed and base layer)
Acknowledgement

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References


