Runoff and Infiltration characteristics of permeable pavements – Review of an intensive monitoring program

Analyse du fonctionnement hydraulique de pavés perméables – compte rendu d'un programme intensif de suivi

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RESUME

Le fonctionnement hydraulique de surfaces équipées a été systématiquement évalué dans un programme intensif de suivi. Le premier objectif de la recherche est d'engendrer une large base de données qui permet le développement d'un module avancé pour modéliser le ruissellement superficiel des pavés poreux. Plus de 150 expériences de laboratoire et de terrain ont été accomplies et analysées pour des caractéristiques d'infiltration et d'écoulement superficiel. Les séries d'expériences incluent plusieurs types de pavés poreux sous diverses conditions aux limites telles que différentes précipitations, plusieurs pentes, et différents degrés d'encrassement. Les résultats représentent une base de données fiable et complète qui permet des conclusions profondes et des recommandations substantielles.

ABSTRACT

The stormwater runoff and infiltration performance of permeable pavements has been systematically evaluated within an intensive monitoring program. The primary objective of the investigation is to generate a broad database which enables the development of an advanced simulation module for urban drainage modelling. Over 150 field and lab scale experiments have been completed and analyzed for surface runoff and infiltration characteristics. The test series include several pavement types under various boundary conditions such as diverse precipitation impacts, varying surface slope and layer construction as well as different stages of surface clogging and several base and subgrade layer characteristics. The results represent a reliable and comprehensive database which allows profound conclusions and substantial recommendations.

KEYWORDS

Minor permeable pavement, surface runoff, infiltration, clogging, HYDRUS.

1 BACKGROUND

Permeable pavements are a common and effective technique to reduce stormwater runoff from urban areas. Various types of more or less pervious structures are available and are used for private as well as for public areas. Consequently, simplified design methods as well as urban drainage models have to reproduce the specific runoff and infiltration processes of these surface structures. However, validated design parameters are rare and the common models are still using ancient methods which have been adopted from the simulation of natural watersheds such as the approaches of Horton or Green-Ampt. Even though permeable surfaces are receiving more and more attention and the expectations regarding the accuracy of model applications are continuously rising, these makeshift methods have not been reconsidered or improved for years. Furthermore, the technical construction of a pervious pavement including base layers significantly differs from natural soils. Therefore, it is not surprising that simulation results show differences of up to 100% compared to observed runoff volume or peak discharge (c.f. Hochstrate or Thorndahl et al.). A lack of adequate methods for the computation of runoff and infiltration processes on pavement structures is obvious; practical approaches which can be easily implemented in common simulation models are needed.

2 MATERIAL AND METHODS

The main objective of the overall investigation is to develop such an advanced approach for modelling stormwater runoff from permeable pavements. Hereto, a profound knowledge regarding the physical processes of stormwater infiltration on and through the pavement construction is essential.

Valuable investigations have been realized in recent years (e.g., Timmermann , Field et al., Pratt et al, Smith or Davies et al.) but are only focusing on particular aspects, do only consider the infiltration capacity of new constructions or do not enable entire water balances, mostly. Overall, more detailed investigations which include the evaluation of the entire percolation processes through top and base layer into the soil layer as well as clogging effects and other impacts are rare. Consequently, further investigations which allow a detailed view into the construction were necessary to obtain a reliable database for the development of a new computational method.

Due to this, an extensive monitoring program has been initiated including field measurements on existing pavements as well as numerous lab scale tests on new and gradually clogged pavements. The overall research project is divided into the following steps:

(1) Field measurements on existing pavements by infiltration tests
(2) Lab scale experiments of several pavement types under various conditions
(3) Data base extension by application of the detailed finite element model HYDRUS-2D on further lab scale scenarios
(4) Evaluation of monitoring data supported by simulation results
(5) Development of an advanced approach on the basis of the monitoring data
(6) Calibration and validation of the new approach against the monitoring data

2.1 Field Measurements

The infiltration capacity of existing pavements and the temporal distribution of the infiltration rate have been evaluated by infiltrations tests. On various sites six different types of permeable pavements have been tested several times using an infiltrometer device (Illgen and Harting, 2006). The collected data indicate the infiltration capacities of the pavement structures after several years of use and enable the evaluation of the spatial and temporal variability of the infiltration rate depending on clogging effects, mechanical impacts by car traffic and the particular weather condition, respectively. In addition, the data are used as reference values for the imitation of clogging effects within the lab scale test series.

The measured values show a high variability between the infiltration rates of a particular pavement recorded at a certain site (different monitoring points on a particular car park or even the same point at different times) as well as between the rates observed at different locations (same pavement at different sites). For instance, the infiltration rates recorded in the centre of a single parking space are significantly higher than on the main traffic or tyre track, where mechanical impacts from cars and the resulting wheel ruts increase clogging. However, surprisingly high infiltration rates have been found at many locations, even on pavements which are generally considered to be hardly permeable and even after long-lasting periods of operation (without sweeping).

An overview of selected monitoring results recorded at a site in Lingen (Germany) is given in Figure 1. At another car park with a pavement consisting of interlocked concrete blocks with a ratio of 8% of gravel filled gaps considerable differences between the infiltration capacity curves of three different parking spaces were observed. Here, the initial infiltration rates amounted to 550, 750 and 1250 l/(s·ha), the final rates varied between 370 and 770 l/(s·ha), all measured the same day.

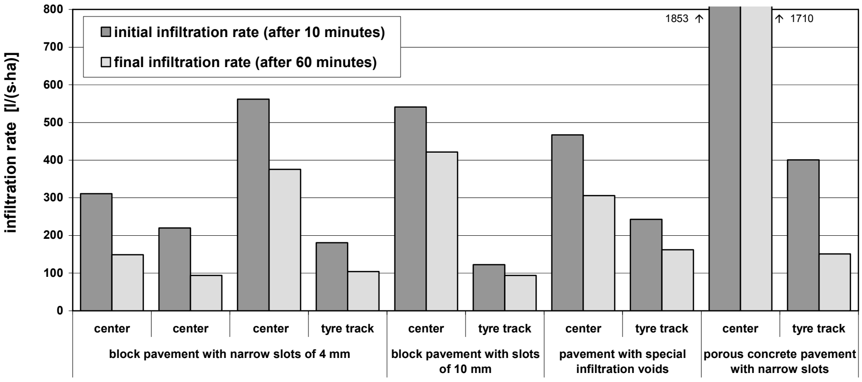

Figure 1. Selected infiltration rates of four different types of pavement measured at a car park in Lingen (Germany)

As expected, clogging effects due to fine material accumulating into the slots or voids are greatly influencing the infiltration capacity and can cause a pointwise decrease of the infiltration rate by factor 10 or even 100 compared to new built pavements. As the process of clogging shows stochastic attributes, probabilistic aspects should be taken into account for any further assessment and detailed recommendations. Admittedly, the recorded data are not sufficient for a probabilistic evaluation yet.

2.2 Lab scale experiments

The major data base for the further evaluation of the runoff and infiltration performance has been generated within an extensive lab scale test series. Several types of pervious pavements have been evaluated under various conditions. Included were experiments of various constructions for diverse precipitation impacts, varying surface slope and layer construction as well as for different stages of surface clogging and several base und subgrade layer characteristics. Over 120 tests have been completed and analyzed for surface runoff, infiltration and percolation rates as well as for changes of volumetric water content at several depths of the base layer.

The test facility is composed of a major steel framework with an integrated hopper and a removable sprinkling unit on top. A steel vat of 1m x 1m x 0.5m contains the entire pavement construction including base layer, bedding layer and pavers and is put on the hopper into the major framework (Figure 2). At the bottom of the steel vat a fine sieve of stainless steel enables an almost free exfiltration of percolating water but prevents erosion of the base layer material. The sprinkling unit provides variable rain intensities between 30 l/(s·ha) and 1000 l/(s·ha) (= 10.8-360 mm/h) and is controlled by an inductive flow meter and a flexible tube pump. Surface runoff is measured continuously by a mechanical tipping counter with a volume of 2.4 litres on a precision balance; drainage flow is collected in a second tipping counter below the hopper outlet and with a volume of 1.8 litres. The volumetric water content in the base layer is observed by time domain reflectometry (TDR) measures. Six TDR probes can be placed in the base layer at various depths and give a profound insight into the main processes inside the pavement construction during sprinkling and during drying periods, also. The monitoring data as well as the actual rain intensity are continuously recorded and processed in time steps of 10 seconds.

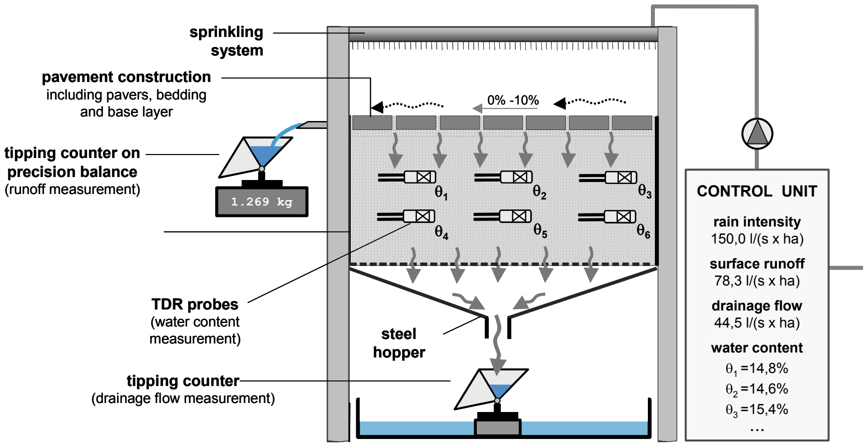

Figure 2. Scheme of the lab scale test facility.

The major advantage of the lab scale test series is the opportunity to evaluate systematically the impact of each single key influence under well defined boundary conditions whereas all other parameters are left unmodified. The impact of the surface slope of a particular pavement, for instance, has been analyzed by experiments with a gradually varied slope of 2.5%, 5.0% and 7.5%, each for several rain intensities.

As old pavements after several years of use cannot be removed, afterwards reconstructed and examined in the test facility without damaging the jointing structure, clogging effects are imitated by the application of silica flour on new pavements. The fine silica powder has proved to be the best alternative to reproduce clogging effects within laboratory experiments (e.g. Davies et al.). Various states of clogging have been considered by dispersion of several amounts of silica flour on the pavement surface. Depending on the type of pavement, amounts between 200 g/m² and 4000 g/m² have been applied and washed into the joints or voids.

To link these amounts to the infiltration capacity of pavements in situ, infiltrometer tests have been carried out in the test facility as well. The resulting infiltration curves have then be compared with our own field measurements and with the results of 49 former infiltrometer tests (c.f. Nolting et al.) as well as with recorded infiltration rates reported in the literature. Thus, it was possible to combine the advantage of clearly defined boundary conditions of the lab scale experiments on the one hand side and the necessity to consider clogging phenomena as they can be found after some years of operation on the other hand.

The lab scale test series comprises the examination of several types of minor permeable pavements with narrow slots (various block and flag pavements), as well as medium permeable pavements with wider joints of 8-15 mm and porous concrete pavement. Extraordinary permeable pavements have not been considered as they are of low relevance for urban drainage management due to their high infiltration capacities. All tested pavement constructions are similar to the pavements investigated within the on-site test series. Moreover, additional experiments have been carried out to examine the impact of a subgrade with a low hydraulic conductivity on the runoff and infiltration performance. Also, the infiltration capacities of various pavements and base layers have been tested in single arrangement without base layer and pavement layer, respectively.

The test matrix of the extensive series of an interlocked concrete pavement with narrow slots of 4 mm is exemplarily shown in Figure 3 and includes 45 single tests. The ratio of joints amounts approx. 4% for this pavement.

		PRECIPITATION IMPACT (IRRIGATION CHARCTERISTICS)					
slope	**stage of clogging**	**2 hours with 100 l/(s×ha)**	**3 hours with 200 l/(s×ha)**	**3 hours with 300 l/(s×ha)**	**3(4) x 30 min each 150 l/(s×ha)**	**30 mm with varying intensity**	**infiltrometer test**
slope 2,5%	new pavement	▨	▨		▨		▨
	200 g silica powder	▨	▨		▨		▨
	400 g silica powder	▨	▨	▨	▨	▨	▨
	500 g silica powder	▨	▨	▨	▨		▨
slope 5%	new pavement	▨	▨				
	200 g silica powder	▨	▨				
	400 g silica powder	▨	▨	▨			
slope 7,5%	new pavement	▨					
	200 g silica powder	▨	▨				
	400 g silica powder	▨	▨	▨			

Figure 3. Test matrix for an interlocked pavement with narrow slots of 4 mm (45 single tests; grey coloured cells indicate one or more tests for the particular boundary condition).

2.3 Data base extension by model application

To extend the data base, the very detailed finite element model HYDRUS-2D is currently applied on further lab scale scenarios. HYDRUS-2D is a modelling environment for simulating the two-dimensional movement of water, heat and multiple solutes in porous media. The program numerically solves the Richards' equation for saturated-unsaturated water flow. The unsaturated soil hydraulic properties are described using van Genuchten, Brooks and Corey as well as modified van Genuchten type analytical functions. The particular lab scale test assembly described above is an ideal application case for the sophisticated HYDRUS-2D model and enables reliable results.

The model is calibrated against the monitoring data and afterwards applied for additional scenarios which have not been considered within the test series. Thus, simulations for additional rain intensities, varying base layer characteristics (thickness, compression, hydraulic conductivity) or different conditions at the beginning of a rain event, for instance, are carried out instead of executing additional time and cost intensive lab experiments. The application of the detailed soil hydraulic model gives the opportunity to densify the database and supports a better understanding of the hydraulic processes within the pavement construction as well.

The simulation results of the volumetric water content θ in a pavement construction over several time steps are visualized in Figure 4. In this example, HYDRUS-2D has been applied on a pervious pavement with slots of 10 mm on a 40 cm base layer of gravel (0/45 mm) for a rain intensity of 100 l/(s·ha).

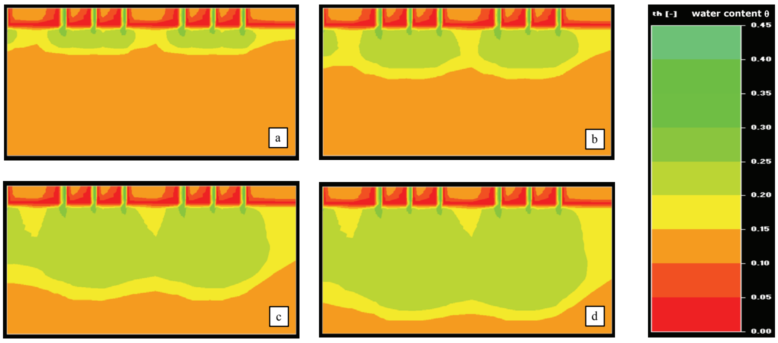

Figure 4. Volumetric water content θ in a HYDRUS-2D simulation on a pervious pavement with 10 mm wide slots after (a) 5 min., (b) 10 min., (c) 20 min., (d) 25 min..

3 DATA BASE ANALYSIS

The monitoring data of the lab scale experiments together with the first simulation results of the HYDRUS-2D application have been analyzed regarding major runoff and infiltration characteristics and their interrelations with the several key parameters such as rain intensity, rain duration, grade of clogging and base layer characteristics (diameter, hydraulic conductivity, density, pore volume).

Mean infiltration and runoff rates from selected tests and their correlation to rain intensity and grade of clogging are exemplarily shown in Figure 5. The results originate from a test series on a pavement with slots of 4 mm on a 40 cm base layer with a slope of 2.5% and are related to constant rain intensities over a period of 20 minutes.

The figure indicates that the infiltration rate of a particular pavement depends on the particular rain intensity even in cases where runoff occurs.

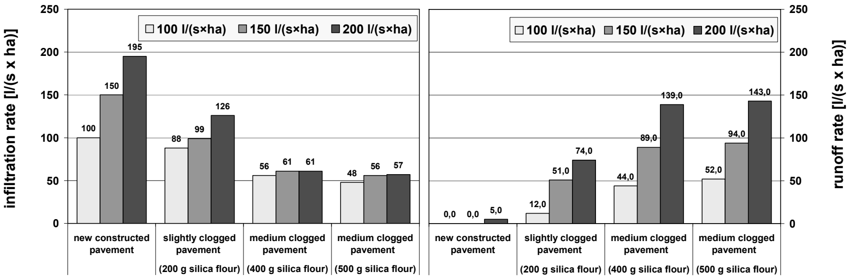

Figure 5. Mean infiltration and runoff rates depending on rain intensity and grade of clogging for a pavement with joints of 4 mm and slope of 2,5% over 20 min. of irrigation.

In comparison to clogging effects and rain intensities, the surface slope of a pavement construction is of lower relevance regarding runoff formation, especially for pavements with higher infiltration capacities or lower degrees of clogging (Figure 6). Also, the particular duration of a rain event has only for short-term events a significant impact. The infiltration rate of a pavement construction decreases during the first 30 minutes mostly and remains more or less constant afterwards.

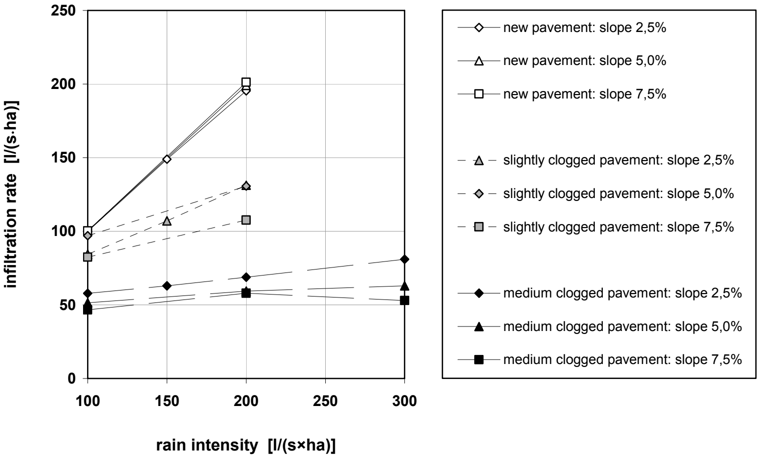

Figure 6. Mean infiltration rates depending on rain intensity, surface slope and grade of clogging for a pavement with joints of 4 mm and slope of 2,5% over 15 min. of irrigation.

The investigated block pavements with slots of 7 and 10 mm, both, showed very high infiltration capacities. Even for tests with large amounts of silica powder only very low runoff rates of 50 and 25 l/(s·ha) were observed for rain intensities of 1000 l/(s·ha).

Even though relatively high rain intensities have been evaluated, the water content below the pavement does usually not reach the state of saturation within a period of 1-2 hours in cases of a free drainage of the base layer. For the scenario of a subgrade with significantly lower hydraulic conductivity, the base layer is functioning as a storage tank with a throttled outflow. In such a case, the water content inside the base layer may rise quickly and can restrict the infiltration into the construction during long-lasting rain events.

The soil water content at the beginning of a rain event is also influencing the runoff and infiltration processes of the pavement construction but on a much lower level than for natural soils. A relatively high soil water content represses the higher infiltration capacities commonly observed at the beginning of a rain event and causes lower and more equal infiltration rates instead. After a dry period of 8 to 24 hours depending on the particular soil and weather conditions the soil water content has reached its initial level and the infiltration capacity has recovered correspondingly. Consequently, the length of a dry period as well as the process of drying itself are important factors and thus not to neglect.

4 OUTLOOK

On the basis of the widespread data set and the therefrom derived empirical relationships, an advanced approach for modelling runoff and infiltration processes of permeable pavements is going to be developed. As the approach should be easy to implement into common urban drainage models, it is planned to work only with a limited number of parameters which are easy to determine. For this reason, a detailed approach as it is implemented in a soil hydraulic model like HYDRUS is not useful. The new approach will be probably based on a simplified bi-directional layer model. In comparison to the common methods used in urban drainage models, as the approach of Horton for instance, the approach will include rain dependent infiltration capacities, the main processes taking place within base and subgrade layers and their interaction with the pavement layer. Clogging will be taken into account by adequate parameter values. Moreover, detailed recommendations for reasonable infiltration rates, runoff coefficients and model parameters are going to worked out which may help planners to estimate the runoff contribution from pavements.

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