Water-permeable pavements as the sole storm water management strategy - problems and possibilities

L'utilisation des revêtements poreux comme unique stratégie de gestion des eaux pluviales – problèmes et opportunités

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RÉSUMÉ

L'utilisation de revêtements poreux comme seule mesure d'infiltration est une option peu encombrante parce que les zones peuvent être utilisées comme routes, trottoirs ou en tant que parvis ou parking. En conséquence, aucune zone supplémentaire ne sera nécessaire pour les systèmes d'infiltration tels que les tranchées, les noues ou les bassins de rétention des eaux pluviales. De plus, les revêtements poreux présentent une évapotranspiration très élevée. En outre, l'augmentation de la recharge de la nappe souterraine présente également un avantage pour recevoir le bilan hydrique naturel. Lors de pluies abondantes ou lorsqu'il y a une augmentation des pluies provenant d'autres zones de surfaces interconnectées, de grandes quantités d'eau doivent être retenues et infiltrées à travers la structure routière aussi rapidement que possible. Cela crée une retenue à court terme qui pose différentes questions :

– Les exigences en matière de force portante de la route sont-elles conservées ? – Les tests CBR (« Taux de Force portante en Californie ») ont montré que la force portante est conforme aux exigences dans tous les cas.
– Quelle quantité d'eaux pluviales peut être retenue dans un mètre carré de structure routière poreuse ? – Selon l'épaisseur de la base et de la sous-base, la capacité de rétention minimum de l'eau se situe entre 63 l/m² et 176 l/m².
- Une adaptation au bilan hydrique naturel est-elle possible ? – La possibilité de recevoir un bilan hydrique proche du bilan hydrique naturel a été prouvée par le calcul de recharge en eaux pluviales.

ABSTRACT

Using water-permeable pavements as the sole infiltration measure is a space saving possibility because the areas can be used as roads, sidewalks or as courtyards or for parking. Thus, no additional areas would be required for infiltration systems such as trenches and swales or storm water retention basins. Furthermore the water-permeable pavements have a very high evapotranspiration. In addition the increased groundwater recharge is also good to receive the natural water budget. In heavy storm water events or when there is increased rainfall from additional inter-connected surface areas, lots of water must be retained and infiltrated through the road construction as quickly as possible. That creates a short-term storage which is the cause for different questions:

- Does the bearing strength requirements of the road conserved? - CBR-tests ("California Bearing Ratio") showed that the bearing strength conforms to the requirements in all cases.
- How much storm water can be store into one square metre water-permeable road construction? – Depending on the thickness of the base and the sub-base the minimum water retention capacity lies between 63 l/m² and 176 l/m².
- Is an adaption to the natural water budget possible? – The possibility of receiving a near natural water budget was proved by storm water recharge calculation.

KEYWORDS

Bearing strength, Permeable pavements, Retention capacity, Storm water management

1 INTRODUCTION

The growing demand for residential areas leads to increasing zones of paved surfaces in urban areas. As a result of this there are problems such as the increase in surface runoff, sewerage overload, decreased groundwater recharge and degraded urban environment due to the reduced evapotranspiration.

Thus compensation areas for infiltration should be created in order to minimise changes in the natural water budget. In this regard water-permeable pavements could be a well solution because of their good groundwater recharge and evapotranspiration rates. The improved evapotranspiration rates compared with standard pavements were verified by a tunnel-evaporation gaupe (Starke et al., 2011).

The short-term storage of storm water can lead to problems because the bearing strength of these roads could be adversely affected by this. Furthermore, it can become even more difficult if there is additional storm water, for example from roof surfaces, which also needs to be drained through the water-permeable road. Therefore, storage and infiltration areas for large amounts of storm water should be made available as part of the road construction (Figure 1). For this reason the required size of the infiltration area must be calculated by several methods for different storm water events, with regard to the permeability of the natural subsurface and for varying thicknesses of the road sub-base. Then the groundwater recharge for the different sized water-permeable pavement areas in a development area needs to be determined so as to compare it with the natural state for finding a natural modified storm water management option.

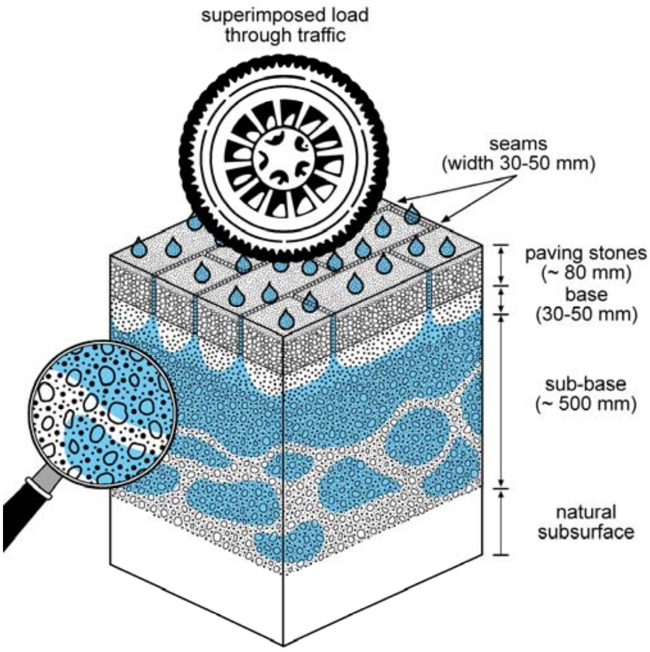

Figure 1: Water-permeable road construction with stored water in the sub-base (drawing by B. Fister).

In the construction of water-permeable roads, attention should be paid to the volume of storm water which needs to infiltrate permanently into the subsurface (FGSV, 2001). Therefore good permeability coefficients of the sub-base and the natural subsurface are very important.

The infiltration rate of water-permeable pavements is 270 l/s·ha which corresponds to a coefficient of permeability of $2.7 \cdot 10^{-5}$ m/s. This value must be doubled because there remain about 50 % of the pores filled with air when the layer is infiltrated from the top downwards, i.e. the required coefficient of permeability is up to $5.4 \cdot 10^{-5}$ m/s (FGSV, 1995).

2 INVESTIGATION AREA

The investigation area for the determination of groundwater recharge is a new development area in Münster-Sprakel, which is a suburb in the northern part of Münster (Northrhine-Westphalia, Germany). The proposed development area covers a total area of 47,980 m² (Table 1). Nearly 120 residential properties in the form of detached and terraced housing, with laterally adjacent garages, will be built. Within the total area different uses have been assigned to individual sub-areas. The partitioning is as shown in Figure 2.

Table 1: Land use in the development area Münster-Sprakel.

land use	area [m²]
street (dark grey)	2,770
side street (light grey)	2,461
accommodation way (rose)	1,119
sidewalk (blue)	1,322
parking area (violett)	887
building (red)	14,445
garage (orange)	1,458
detached house	520
terrace/garden path	3,120
open space	19,878
total area (green-rimmed)	**47,980**

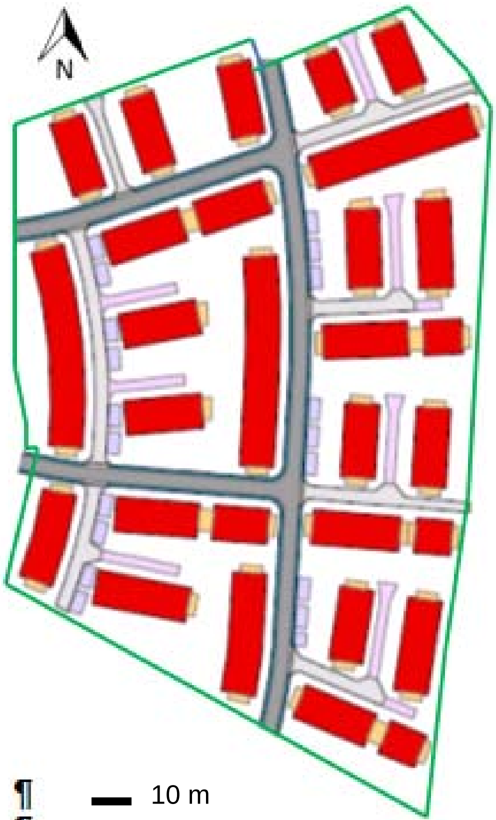

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Figure 2: Partitioning of the development area Münster-Sprakel with ArcGIS.

The Münster-Sprakel development area is located in climate zone 5 (Meßer, 2010), with a potential evapotranspiration of between 540 mm/a and 580 mm/a and a precipitation rate of 800 mm/a. The soil in this area is a podzol-gley which corresponds to a sandy soil in the calculation tables from Meßer (2010) and is quite water-permeable. The depth to the groundwater table is between 2 m and 3 m and is thus ideal for the installation of water-permeable pavements. Also beneficial is the minimum slope ranging from 0 % and 2 %.

3 METHODS

The bearing capacity of the base material used for short-term storage of water within the road structure was investigated by CBR-tests ("California Bearing Ratio"). In the tests the soil strength was measured by pushing a metal bar (diameter = 50 mm) to a depth of 10 mm into a compacted sample of the sub-base material. For reproducing the capacity for storm water retention in the sub-base, the soil samples were compacted in the proctor pot (inner diameter = 150 mm) (DIN 18 127, 1997) and then irrigated with various amounts of water to simulate different storm water events (Table 2: storm water event 0-5).

For calculating the minimal water retention capacity of the water-permeable road construction the preestimated values using Hoferichter (2010) were supplemented so as to get an overview of the possible additional connection area which could be drained over the water-permeable road if the water storage efficiency had been already exhausted by previous storm water events. In this process the entire road structure, consisting of paving stones, seams, base and sub-base, was included. (Note that these calculations refer only to one square metre of water-permeable road construction and not to the investigation area.) The precipitation values used for the capacity calculations are based on design rainfall as defined in regulations (DWD, 1997) (Table 2: single and double design rainfall) and on the storm water events which have been simulated by watering of the samples for the CBR-tests (Table 2: storm water event 0-5).

Table 2: Different storm water events with the associated precipitation rates.

storm water event	**watering the sample in the proctor pot (prior to the CBR-tests)** [ml]	**Precipitation rate during about 10 minutes** [l/m²]	**intensity of the storm water event** [l/min·m²]
single design rainfall		16.19	1.62
0	345	19.52	1.95
1	395	22.35	2.24
2	405	22.92	2.29
3	415	23.49	2.35
4	430	24.34	2.43
5	445	25.18	2.52
double design rainfall		32.43	3.24

In addition to the storm water events the permeability coefficients of the subsurface are very important for the amount of storm water which can infiltrate through the water-permeable pavement or be retained by short heavy rain events, and also has an effect on the capacity to accommodate an additional adjacent surface. The varying thickness of the sub-base (between 0.5 m and 1.5 m) also influences the size of such adjacent surfaces.

For the determination of the groundwater recharge after Meßer (2010), an area calculation was carried out initially on the individual land use types based on a development plan for the different used and paved surfaces in the investigation area using ArcGIS (Figure 2 + Table 1). Then values for the evapotranspiration (mm/a), and for the direct runoff fraction (i.e. percentage of total outflow) using tables of Meßer (2010), were assigned to the different used and paved surfaces. Using these values the groundwater recharge for various scenarios (Table 3) in the development area was determined. Therefore streets, side streets, sidewalks and parking areas variantly designed impermeable, water-permeable and evaporation optimized (Table 3). Although the evaporation factor of the areas varies between 1.4 for only water-permeable designed pavements and 2.4 for water-permeable and evaporation optimized pavements (Göbel et al., 2013). On the basis of these values the scenario which is as similar as possible to the natural state (i.e. field conditions) should be chosen.

Table 3: Different scenarios for the determination of the groundwater recharge.

scenario	thickness of sub-base [m]	streets 2,770 m²	side streets 2,461 m²	sidewalks 1,322 m²	parking areas 887 m²
0 - field	-	-	-	-	-
1 -development plan	0.5	impermeable	impermeable	impermeable	impermeable
2	0.5 – 1.0	water-permeable (1.0 m)	water-permeable (0.5 m)	impermeable	impermeable
3	0.5 – 1.0	water-permeable (1.0 m)	impermeable	water-permeable (1.0 m)	water-permeable (1.0 m)
4	0.5 – 1.0	water-permeable (0.5 m)	water-permeable (0.5 m)	water-permeable (0.5 m)	water-permeable (0.5 m)
5	0.5 – 1.0	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)
6 - all roof areas treated as additional adjacent surfaces	0.5 – 1.0	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)
7 - 50 % of the roof areas treated as additional adjacent surfaces	0.5 – 1.0	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)	water-permeable + evaporation optimized (0.5 m)

4 RESULTS AND DISCUSSION

The values of the CBR-tests were calculated from the strength-depth-curves. The strength at 2.5 mm and 5.0 mm penetration depth were tapped and divided by a reference strength which is for a 2.5 mm penetration depth 13.2 kN and 20 kN for a 5.0 mm penetration depth. According to the “Technischen Prüfvorschriften für Boden und Fels im Straßenbau” (FGSV, 1988) the measured strength for the calculation values of the CBR-tests is normally elected at 2.5 mm penetration depth. If the calculated values at 5.0 mm penetration depth are still greater after repeating the tests, these values are chosen for standard. In this connection this was always the case and so the 5.0 mm values are used for all calculations. The values of the tested samples were within the expected range of more than 50 %. Thus the requirements for bearing strength are fulfilled for all simulated storm water events.

The minimal water retention capacity was then calculated for one square metre. Based on the minimal water retention, the size of ‘an additional adjacent surface’ was determined in terms of what can be drained through one square metre. The best permeability was a medium sandy soil with an infiltration capacity of 3 l/min·m which, in combination with a sub-base thickness of 1.5 m, provides the largest additional adjacent surfaces. Depending on the intensity of the storm water events (Table 2) the additional adjacent surface has an area of size between 42 m² and 93 m³ (Figure 3). Consequently the smallest additional adjacent surface has the lowest permeability with an infiltration capacity of 0.0003 l/min·m. The possible connection area decreases even more when the thickness of the sub-base is only 0.5 m. In that instance the size of the additional adjacent surface is between 5 m² and 21 m² (Figure 3) according to the intensity of the storm water event (Table 2).

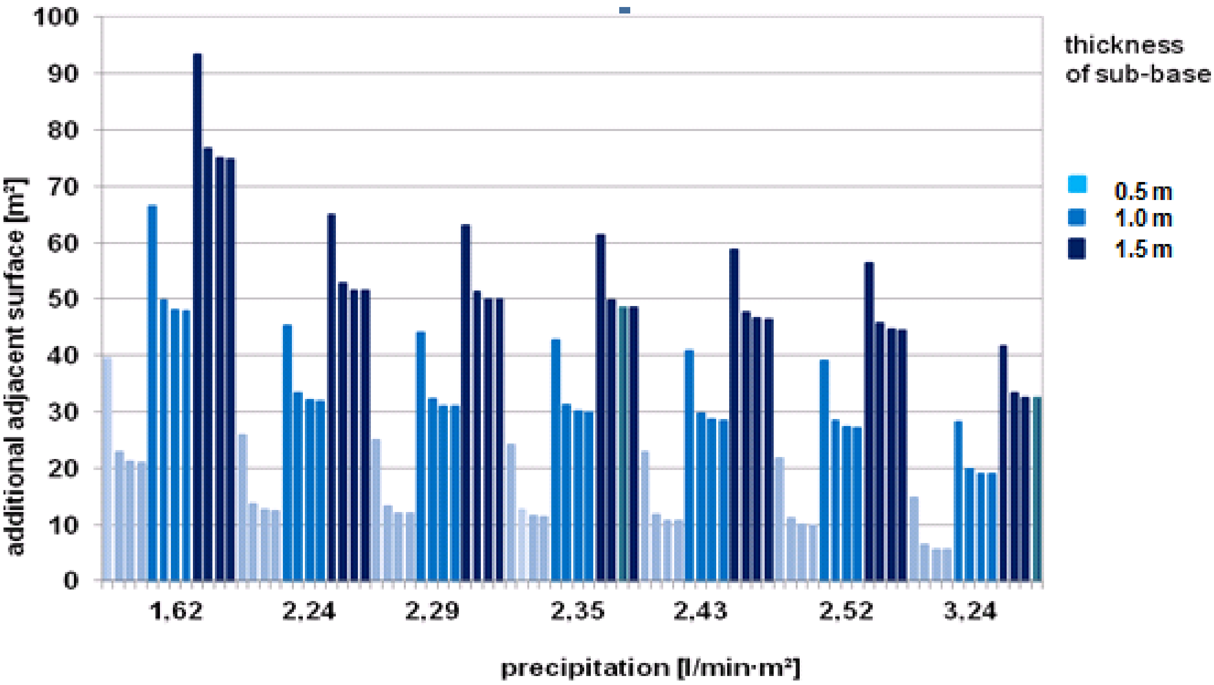

Figure 3: Additional adjacent surfaces of different thicknesses of the sub-base (permeabiltity of the natural subsurface, represented by the four bars pro thickness (3.0 l/min·m²; 0.3 l/min·m²; 0.03 l/min·m² und 0.0003 l/min·m²).

The results of the groundwater recharge by Meßer (2010) for the development area Münster-Sprakel, Germany, based on the climate, the sub-surface and the depth to water table because the direct runoff and the evapotranspiration are influenced by them. Figure 4 shows the groundwater recharge of the different scenarios:

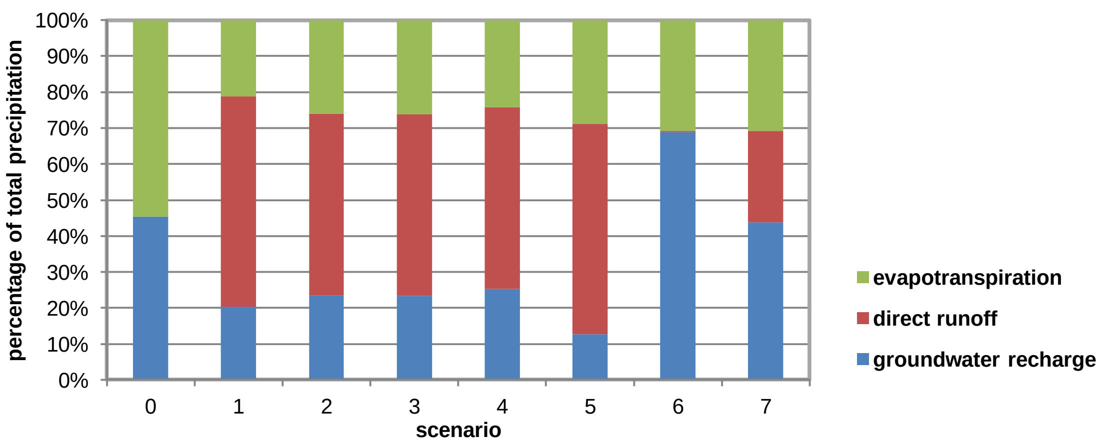

Figure 4: Groundwater recharge of the different scenarios of the development area Münster-Sprakel.

According to these results (Figure 4) scenario 7 (Table 3) with a groundwater recharge of 350 mm/a is the closest to the natural state with a groundwater recharge of 363 mm/a at a total precipitation of 800 mm/a. But there are also scenarios with a higher groundwater recharge then in the natural state which can lead to an increasing groundwater level.

5 CONCLUSIONS

Water-permeable pavements can be used as the sole measure of storm water management. Based on laboratory tests the soil bearing strength fulfilled the necessary criteria even after a short-term storage of water. The water retention capacity, according to the calculations, is also sufficient for the storm water retention of the additional adjacent surfaces.

All results were obtained only for stationary states. The behaviour under dynamic loads should still be observed in a test setup with a larger scale, such as a pilot street, over a longer period.

Furthermore, it should be thinking about emergency measures to protect against flooding of streets and surrounding estates during extreme storm water events. Various possibilities would be: Shallow grooves for derivation in the middle of streets, elevated edge stones or combinations of the water-permeable pavements with other infiltration systems such as trenches, swales and shafts.

A cost calculation for the water-permeable pavements as sole infiltration area without additional drainage measures have already been carried out and showed that the costs are slightly less than the costs of a conservative development. In further cost calculations the emergency measures and the combination with other infiltration systems as well as the specific maintenance and construction conditions should be involved.

ACKNOWLEDGEMENTS

Many thanks go to the “Fachhochschule Münster”, Germany, especially to Prof. Dr. H.H. Weßelborg, I. Fenneker, D. Kaiser and F. Stegner for the assistance in the laboratory work. For providing the sample material I thank the “Heinrich Klostermann Betonwerke GmbH & Co.KG, Coesfeld, Germany. Further thanks go to Dr. J. Meßer for the support in the calculation of groundwater recharge in the development area Münster-Sprakel, Germany.

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