Evaporation measurements on enhanced water-permeable paving in urban areas

Patricia Göbel [1], Phillip Starke [1], Wilhelm G. Coldewey [1]

[1] Division of Applied Geology, Geological Institute, University of Münster, Correnssstr. 24, D-48149 Münster, Germany (angeo@uni-muenster.de / Phone: +49-251-8333941)

Author address (starkep@uni-muenster.de)

Abstract

Pavements consisting of water-permeable paving stone have a certain retention and storage capability for rainwater in the event of intense rain. Applied on a large surface, this results in a mitigation of flood events. Compared to an impermeable surface area, the surface flow rate decreases while groundwater regeneration increases. To date, the actual change in the third water balance parameter, evaporation, is unknown. The man-made urban water cycle can more closely resemble the natural water cycle by increasing evaporation.

The aim of the project described on the following pages is to vary and optimize the characteristics of water-permeable pavements (structure and constitution of the road base, underlay, structure and constitution of the paving stones used, width and filling of the seams, etc.) taking into consideration the applicable regulations, in such as way as to achieve evaporation rates that are as high and as constant as possible. The extensive future use of optimized products and pavings could improve the city climate and counteract the increased incidence of flood events.

Measurement of the effective and active evaporation rate was carried out using a newly-developed tunnel evaporation gauge (WEIß et al. 2002). This measurement technique detects the actual evapotranspiration over plane, overgrown and non-overgrown surfaces. In the course of running-in the tunnel evaporation gauge, it was possible to gather first results.

Keywords

soil sealing, evaporation, pervious concrete, unsealing, water-permeable paving

Introduction

As a result of reduced infiltration and reduced evaporation, sealed areas are characterised by an increased surface flow. The natural water cycle is changed and it adjusts to the so-called urban water cycle which is characterized by high surface flows. In particular river systems characterized by a high degree of sealing in the catchment area, show an increased incidence of flood events. These are in fact man-made and not natural disasters.

During the past decades, climate changes have been causing an increase in precipitation rates in the northern hemisphere (ZHANG et al. 2007). In addition, intense rain events are occurring more frequently and there is an increase in winter rain as a result of less snowfall in mild winters. This will therefore lead to a further intensification of flooding problems. Hence, it is not enough to put a stop to soil sealing, but rather an unsealing of existing sealed surfaces is also absolutely essential. Furthermore, special flood prevention measures are also required. New, man-made retention areas should more closely align the urban water cycle to the natural water cycle.

Both advantages are combined in water-permeable pavements made of pervious concrete. Pavements that have been designed with water-permeable paving stone can minimize the surface flow by infiltrating rainwater. The water seeps and causes groundwater regeneration.

For a short time, it abandons the surface flow. A part of the water is held within the structure and is available for evaporation into the atmosphere. The surface flow is therefore delayed or even decreased in two ways: These effects are to be analysed in the course of this research project, which is supported by the German Federal Environmental Foundation ("Deutsche Bundesstiftung Umwelt", Az. 23277-23). The aim of the project is to optimize the characteristics of water-permeable pavements (structure and constitution of the road-base, underlay, structure and constitution of the paving stones used, width and filling of the seams, etc.) taking into consideration the applicable regulations, in such a way as to achieve evaporation rates that are as high and as constant as possible.

The report on hand was generated in the course of the running-in of the gauge for measuring actual evapotranspiration. It shows first trends.

Methods

In order to run-in the measuring system, two conventional pavement areas were compared. Area 1 was impermeable, area 2 was water permeable. The areas were set up in Coesfeld, Germany by dismantling an existing parking lot surface. The paving stones and the structure of this impermeable area were partly replaced by a conventional water-permeable structure and paving stones. This replaced area represents area 2.

The installation of Area 2 was carried out compliant with general technical approval (DIBT 2006, license number Z-84. 1-2). The underlay material was a 0/45 hard limestone gravel. Compressed in several layers, the underlay was 1 m deep. This depth was due to the highly impermeable subsoil. The paving stones were imbedded into the 3 cm underlay, consisting of 2/5 hard limestone gravel. To complete the water-permeable pavement area, a 1/3 basalt grid was placed into the seams. These three installed aggregates were analysed with respect to their granulometry, grain geometry and proctor density. Furthermore, a frost-alternating test was carried out to assure that all the installed materials were up to standard. In the course of the project, an examination of the potential effects of the structure on the evaporation rate is also planned. All the test methods applied during the project are standardized according to the EN Standards. All the tests carried out were strictly in line with these standards. The standardised water-permeable structure enables a comparison between area 2 and any other water-permeable pavement areas. Consequently, area 2 also serves as the standard and reference area for future measurements.

Laboratory experiments looking at the evaporation in the embedded paving stone (geoSTON® protect, manufacturer: Heinrich Klostermann Betonwerke GmbH & CO. KG, Coesfeld, Germany), were intended to simulate the evaporation process for geoSTON® protect. This paving stone was selected as it is the only pervious concrete paving stone in Germany, which has general technical approval. This approval admits the stone for use in surface coverings to treat and infiltrate precipitation run-off in traffic areas (DIBT 2006). Hence, the geoSTON® protect's field of application is wide-ranging: In addition to pavements and cycle lanes, it can also be used for less frequented streets with a maximum of 5,000 cars per day. The laboratory tests on the geoSTON® protect focussed on its porosity volume, retention capacity and evaporation rates at pre-defined saturation levels of the stone. These three factors were considered to be the most important with respect to outdoor evaporation rates. In order to ensure that permeability ($k_f \geq 2.7 \times 10^{-5}$ m/s) is fulfilled, permeability tests were carried out. In the field tests, by way of comparison, evaporation measurements were carried out over both areas. For this, the tunnel evaporation gauge (german: Tunnelverdunstungsmessgerät = TUV), developed by Prof. Dr. Werner at the University of Münster, Germany, was used. This apparatus can detect the actual evapotranspiration over plane, overgrown and non-overgrown surfaces. By means of a lifting arm, the pivoted tunnel (a plexiglass halfpipe opened on both sides) is set down alternately on the neighbouring areas. The intermittent measuring operation ensures that each of the two measuring areas is only covered by the tunnel for 10 minutes per hour. In this way, precipitation, insolation and ventilation are barely affected (WERNER 2000, WEIß et al. 2002). Ventilators inside the tunnel produce an air flow which runs longitudinally through the tunnel while it is lowered on a measuring area. The wind speed in the tunnel is controlled by an external wind sensor. Per period, the humidity of the air flow increases on its way from the inlet to the discharge opening of the tunnel.

Figure 1: Lateral view of the TUV with opened control cabinet, to the left area 1 and to the right, area 2

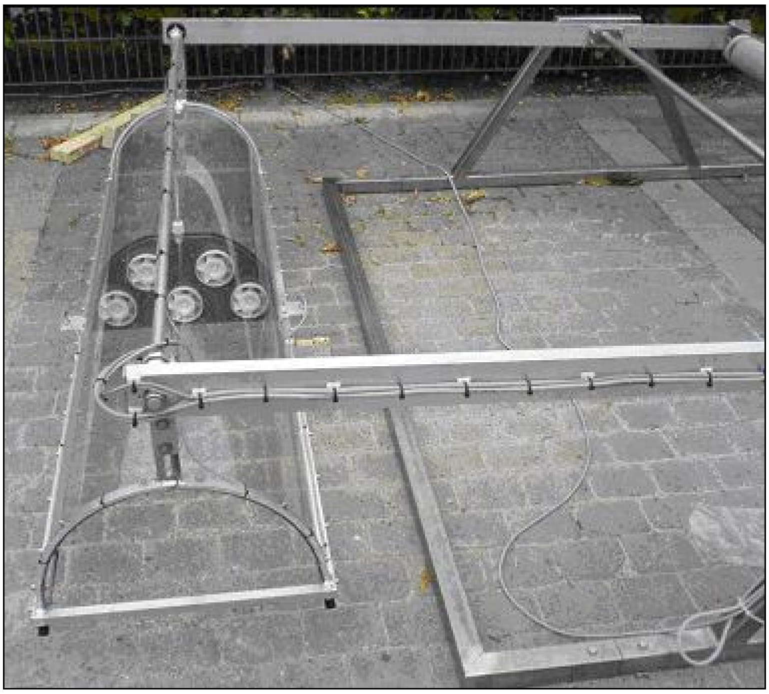

Figure 2: TUV tunnel in lowered position over area 1

The difference in the relative humidity of the incoming and outgoing air is determined by means of two humidity sensors at the start and the end of the tunnel. Using this data, the TUV calculates the actual evapotranspiration by applying the following formula:

$$ET_a = \frac{ct_1 \cdot \bar{v} \cdot e_s \cdot (U_2 - U_1)}{10^3 \cdot \left(1 + \frac{\bar{T}}{273}\right)} \qquad \text{(Formula 1)}$$

ET_a	actual evapotranspiration (mm)
e_s	saturation vapour pressure (hPa)
U_2	humidity sensor 2
U_1	humidity sensor 1
ct_1	apparatus constant (ct1=0.757)
$\bar{T}$	average temperature (°C)
$\bar{v}$	average wind force, detected by the external wind sensor (m/s)

(UIT 2007)

Preliminary tests of the TUV on lysimeters have shown a high accuracy of measurement (Werner 2000, Weiß et al. 2002). The use of standard methods such as lysimeters or tensiometers in this project would have been very expensive and error-prone. Hence, for this experimental series, the TUV was identified as the ideal solution.

The TUV was placed between both measuring areas, so that the tunnel could be lowered on both areas alternately, enabling a real-time comparison between both areas (only 6 minutes between two measurements). In order to establish the relation between evaporation and precipitation, a self-recording raingauge was installed in close proximity to the TUV.

Results and discussion

Results from the laboratory test, show that the tested structure materials used in area 2 comply to the rules. Most of the parameters tested are consistent with the manufacturer’s declaration of conformity. The seam material (1/3 basalt grid), the underlay material (2/5 hard limestone gravel) and the layer material (0/45 hard limestone gravel) were tested. The seam and underlay materials fulfil all requirements according to DIBt (2006). Their permeabilities (k_f = 1.8 x 10^{-4} m/s and k_f = 2.87 x 10^{-4} m/s) are significantly above the required minimum of k_f = 5.4 x 10^{-5} m/s. The layer material shows differences with respect to the required granulometry. The grading curve is too coarse grained, which can probably be attributed to a mistake during sampling. Presumably, samples were only taken at the margin of the material heap. This is not in keeping with the EN Standard DIN EN 932-1 (1996), which requires that most samples be taken from the centre of the material heap. Grains at the margins of heaps are mainly coarse grained as a result of demixing processes. All in all, the embedded structure of area 2 is viewed as representative of existing water-permeable pavement areas with this composition. An infiltration measurement on area 2 confirmed the required water permeability. A 10-minute infiltration rate of 4400 l/(s x ha) is more than tenfold the required 270 l/(s x ha). Only 35 l/(s x ha) can infiltrate area 1, thus this area is viewed as nearly impermeable.

The laboratory tests on the geoSTON® protect show that the stone exhibits a high water-retention capacity. Practically the entire pore volume can be saturated before water seeps. The average porosity of the stones is about 7.8 % volume. The geoSTON® protect is able to retain 4.6 mm of precipitation. This quantity of water is equivalent to about 95 % of the total average porosity capacity. Results of laboratory evaporation measurements show that evaporation mainly takes place in the upper part of the stone. Although water in the bottom pores of the stone is also available for evaporation, the laboratory results show that with increasing distance to the top of the stone, evaporation rates decrease significantly.

The outdoor evaporation measurements over both areas started at the end of July 2007. In the second week of measuring, first clear trends could be detected. Following precipitation, more water was evaporated over area 2. As was the case in the laboratory tests, the evaporation rates weakened as the surface dried. The evaporation rates for area 1 were not as high. The evaporation was lower, but more continuous. With respect to the normal daily profile, the evaporation rate for area 1 is actually higher, and the total summer evaporation is higher too. Table 1 provides basic information concerning the evaporation measurements, which were carried out over three periods.

Table 1: Evaporation measurement overview

Date	Duration	Logged	Characterisation of the measurement-period	Observed evaporation rates
from - to	(h)	(%)		
24.07.07 – 17.08.07	587	43.8	summer	area 1 > area 2 on dry days area 2 > area 1 after precipitations
18.08.07 – 15.10.07	542	61.1	calibration	area 1 = area 2
15.10.07 – 16.12.07	1512	44.1	winter	area 2 > area 1
	2641	47.8	amount	area 1 > area 2
repair work				

During the second measuring period (17.08.2007-15.10.2007), reference measurements were carried out. External influences, such as air deflection caused by a hedge located near the testing ground or possible shadowing by this hedge, could affect the comparability of both areas. For this calibration, the areas were covered with an identical covering. In this instance carpet with gum-underside was used, because of its water-impermeability and the (small) retention capacity between the fibres. Thereby it was possible to exclude errors caused by external factors by means of this calibration. Evaporation over the area 1 carpet was the same as evaporation over the carpet on area 2. During the course of the measurements, the TUV logger unit had several malfunctions resulting in data gaps interrupting the continuous measurement. Despite several repairs, the defect in the logger unit could not be rectified. Thus, evaporation data was only logged for 47.8 % of the measurement period.

During the third period, the carpets were removed and the comparative measurements were continued until 16.12.2007. Compared with the summer results, the winter evaporation rates for area 2 were higher than those for area 1 (see fig. 3 and fig. 4). Similar to the summer measurements, the highest evaporation on area 2 was detected after precipitations. The evaporation rate for area 1 again proved to be more continuous. As a result of a higher number of precipitation events, the total winter evaporation is higher for area 2. A further reason for the reversal in the levels of evaporation might be the moss and grass vegetation in the seams. Area 1 existed before area 2 was installed. During this time, vegetation could grow in the seams. In particular in the summer, this vegetation can actively increase the evaporation from area 1 as a result of transpiration. In winter, there is a seasonal decrease in these grasses. As a result, the evaporation rates for the two areas resembled each other more closely during dry periods.

During both measuring periods (summer and winter), the evaporation on area 1 was somewhat higher. However, an actual comparison was difficult to arrange due to the unequal preconditions.

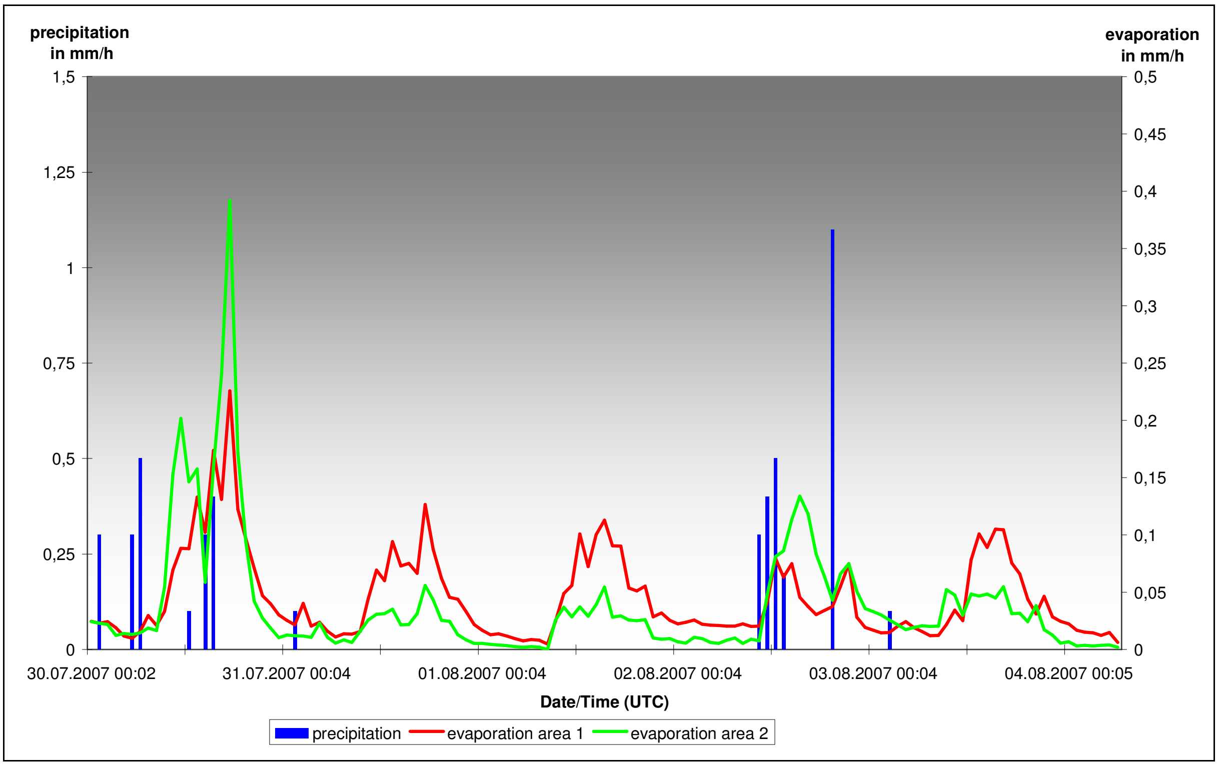

Figure 3: Precipitation and evaporation rates, 30.07.2007-04.08.2007

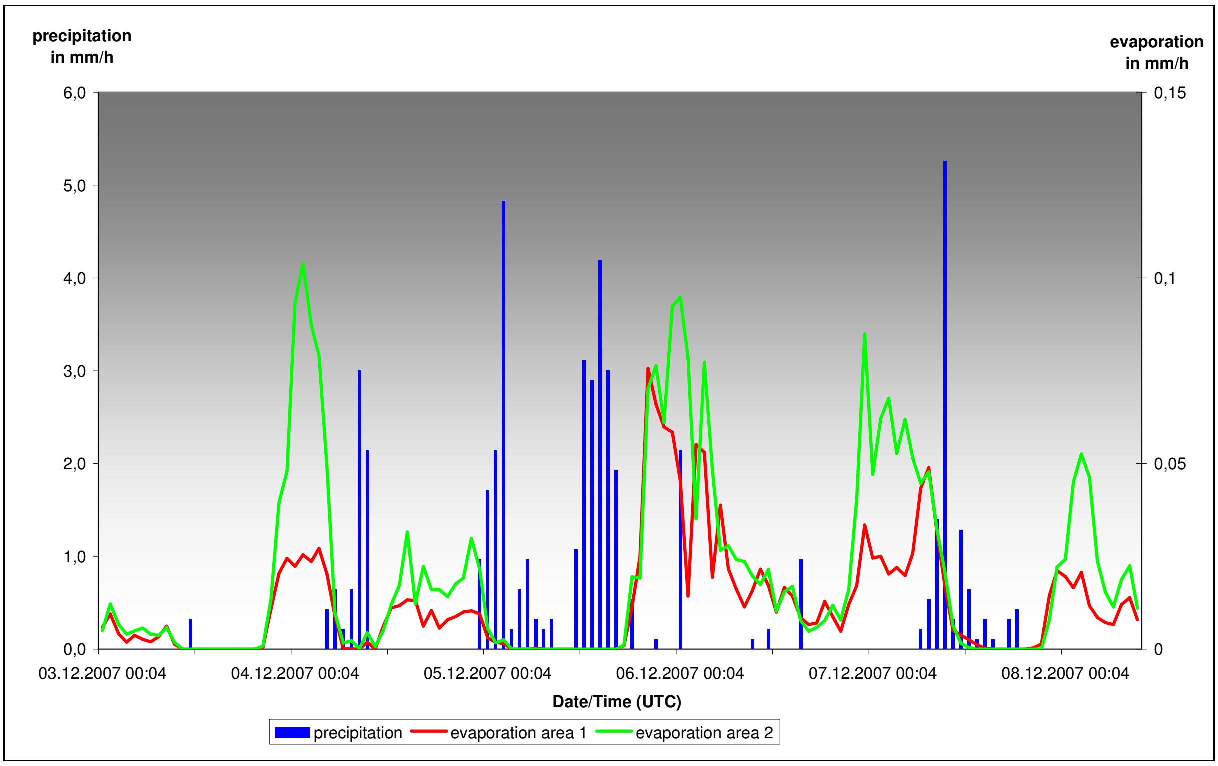

Figure 4: Precipitation and evaporation rates 03.12.2007 - 08.12.2007

Conclusions

The running-in of the gauge was successful. As a result of the defective logging function on the TUV, about 52.2 % of the evaporation data could not be logged. From the remaining 47.8 %, the following trends can be derived and these will be used in the project. Other potential sources of error, which might have affected evaporation measurements, such as unequal wind break or shadowing from the hedge, were adjusted or excluded. In January 2008, the defect in the TUV was repaired successfully, and consequently errors caused by the gauge, can now be excluded too. Any future measurements in the project will not contain data gaps.

The water permeable area was installed correctly according to the common standards. Detailed testing of the structure materials from a building material point of view attested their suitability. The infiltration rate (4400 l/(s x ha)) was verified by means of a permeability test. General trends, like a higher evaporation over the impermeable area on dry days, allow for the influence of seams and vegetation on the evaporation. As a result, the water impermeable area shows the higher average evaporation rates. This applies especially in the summer, when transpiration from the seam vegetation adds to the evaporation. The newly-installed water permeable area was entirely devoid of vegetation. Despite these unfavourable preconditions, the water permeable area nonetheless showed higher evaporation rates after precipitations albeit for a short time.

It can be assumed that the underlay also influences the evaporation processes. The laboratory results for geoSTON® protect show that even the water in the lowest pores is available for evaporation. Whether or not the base layer material influences evaporation could not yet be clarified.

Future prospects

In the course of the project (DBU, Az. 23277-23), the influence of the structure and the seams on evaporation will be measured. To achieve this, seven hexagonal pavement areas will be installed. The middle reference area will be configured identical to the waterpermeable area during the running-in period. The other pavement areas will be installed around this area. These will be individually arranged. One area will only allow evaporation via the seams. It will thereby analyse the extent of seam evaporation. Variations in the underlay or layer material in other fields will show the influence of these materials. By using colour variations of geoSTON® protect, it will be possible to track the influence of changes in the stone on evaporation. These pavement areas will be measured over a period of one year. During this first year, the focus will be on the influences of the structure and seams. Following this, the areas will be replaced by new pavements. Building on the knowledge collected during that first year, new areas will be installed. In the following year-long measuring period, further variations to the stone will be researched.

Project researchers will thereby be able to make targeted recommendations with respect to future water-permeable road building. This will include defining the best construction designs which allow for the highest evaporation rates. The project will produce highly valuable information that can make a significant contribution to the improvement of city climates and the reduction of flood events.

Acknowledgements

This research project was sponsored by “Deutsche Bundesstiftung Umwelt” (DBU; “The German Federal Environmental Foundation”; Az. 23277-23)

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