Effects of different water-permeable pavement designs on evaporation rates

Conséquences de différentes conceptions des pavés poreux sur les taux d'évaporation

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RÉSUMÉ

Il est possible d'améliorer le bilan hydrologique des zones urbaines par le biais des chaussées perméables. En effet, ces chaussées perméables présentent un taux d'évaporation de 16% supérieur à celui des chaussées imperméables, ce qui peut améliorer le climat urbain. La surface des chaussées et les couches plus profondes influencent les taux d'évaporation. Si l'on compare les taux d'évaporation de différents systèmes de chaussées perméables, la distribution granulométrique de la couche d'assise n'a pas d'influence significative sur les taux d'évaporation. Au contraire, une couche d'assise composée d'un enrobage double réduit l'évaporation de 16% par rapport à une couche d'assise homogène. En changeant la couleur des pavés, une augmentation des taux d'évaporation de 19% peut être atteinte. Une autre comparaison montre que l'effet de transpiration de l'herbe des chaussées herbeuses entraine des taux d'évaporation trois fois supérieurs à ceux obtenus avec des chaussées en béton perméable. Il est impossible d'atteindre des taux d'évapotranspiration aussi élevés avec une chaussée en béton perméable. Malgré cela, l'utilisation largement répandue des chaussées en béton perméable continue à avoir un impact sur le climat urbain.

MOTS CLÉS

Taux d'évaporation, recharge des nappes phréatiques, chaussées perméables, climat urbain

ABSTRACT

The urban water balance can be attenuated to the natural by water-permeable pavements. Furthermore, water-permeable pavements have a 16% higher evaporation rate than impermeable pavements, what can lead to a better urban climate. Evaporation rates from pavements are influenced by the pavement surface and by the deeper layers. By a compared evaporation measurement between different water-permeable pavement designs, the grain size distribution of the sub-base shows no influence to the evaporation rates in a significant way. On the contrary, a sub-base made of a twin-layer decreases the evaporation by 16% compared to a homogeneous sub-base. By a change in the colour of the paving stone, 19% higher evaporation rates could be achieved. A further comparison shows that the transpiration-effect of the grass in grass pavers increases the evaporation rates more than threefold to pervious concrete pavements. These high evapotranspiration rates can not be achieved with a pervious concrete paving stone. In spite of this, the broad field of application of the pervious concrete paving stone increases the importance in regard to the urban climate.

KEYWORDS

Evaporation rates, groundwater recharge, water-permeable pavements, urban climate

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1. INTRODUCTION

The use of water-permeable pavements (WPPs) can help prevent sewage overflows and floods in urban areas because such pavements allow the infiltration of water directly into the ground. The amount of precipitation water depends on the local climate, and therefore drainage needs must be adapted to suit climatic conditions (Dawson, 2009). Depending on the local climate and the permeability of the pavement, there might be no need for a canalisation or any further infiltration facilities.

The large-scale use of these pavements, will lead to a change in the urban water balance as the surface runoff from impermeable surfaces is prevented and the infiltration rate is increased. In addition, Starke et al. (2009) established that evaporation rates for WPPs made of pervious concrete were 16% higher compared to water-impermeable pavements. The urban water balance is approximated to the natural water balance. With large-scale use, the higher evaporation rates can lead to a cooling effect in cities. On WPPs, the evaporation rates are not just higher, the more important effect is that theses rates are more evenly distributed over time (Starke et al. 2009). The urban typical rain-air humidity interconnection (Kuttler, 2008) and the resulting weather, like sultriness or dry heat (urban heat island effects), can be attenuated.

It is assumed, that these higher evaporation rates result mainly from the water retained in the pore matrix of the paving stone and inside the seam filling. The effect of the deeper layers, like the sub-base, is unknown but as Lay (1986) presented, evaporation of deeper street layers also exists. On impermeable streets, this vapour can reach the atmosphere just via cracks, which minimizes the influence on the total evaporation. WPPs are also permeable for vapours and gases and through a higher vapour transport from the sub-base into the atmosphere, the effect could be significant. The more evenly distributed evaporation rate, even after several dry days and a dry pavement surface, can be a sign of an influence of the deeper street layers on the evaporation rates (Starke et al. 2009), which layers are made of granular materials with defined grain size distributions (Ferguson, 2005). The effects on evaporation rates from a variation in the grain size distribution and the associated variation in its hydraulic and physical attributes have not been researched yet.

In this paper, the evaporation rates of WPPs with different sub-base materials are compared. In addition, a variation in the paving stone colour and a comparison to a grass paver give an informative basis for assessing how far it is possible to increase urban evaporation rates by the use of different WPP types. The aim of this paper is to show how evaporation rates of WPPs can be increased, to influence urban climate in a positive way.

2. METHODS

2.1. Laboratory

Göbel et al. (2008) shows that evaporation comparisons between different ages of pavements is hardly possible and therefore all tested pavements were newly constructed. To get reproducible and practicable results, the first step was an investigation of existing materials for street building. 27 loose and conventional materials in this particular market sector were collected and were tested for their hydraulic and physical attributes. All laboratory tests are standardized and were carried out according to strict to procedures. In this paper not all realized tests are discussed. The main focus is on the water retention capacity ($wrc_{\mathrm{mat.}}$ for single materials and $wrc_{\mathrm{pav.}}$ for the material in regard to its part of the whole pavement), the permeability (k_f, the main attribute for a WPP) and the height of capillary rise ($h_{\mathrm{cr.}}$). These hydraulic attributes are complemented by some physical attributes like the grain shape (*SI* for Shapeness-Index and *FI* for Flakiness-Index) and the Proctor-density (ρ_w). The Proctor-density reflects the density conditions of the material in the field. The hydraulic laboratory tests were realized with ρ_w to get realistic results. The accomplished tests and their corresponding rules and standards are picked up again in Table 2.

Based on all realised results, plotted in a special format, the suitability, for water-permeable street building can be verified. Only the suitable materials were used in the field test. Up to now, a laboratory testing method for material-specific evaporation rates does not exist. In the course of the research project a lab-testing device was developed and is actually in the testing phase.

2.2. Outdoor test

In Coesfeld, Germany, a test field was built (Figure 1, right side) consisting of seven hexagonal areas. All areas are divided from the others by plastic 'walls' that extend from 1 cm above the paving stone surface to the bottom of the sub-base (620 mm below the surface). The central reference area (Area 2.1) is constructed in accordance with the approved national technical specification for Germany (DIBt 2006).

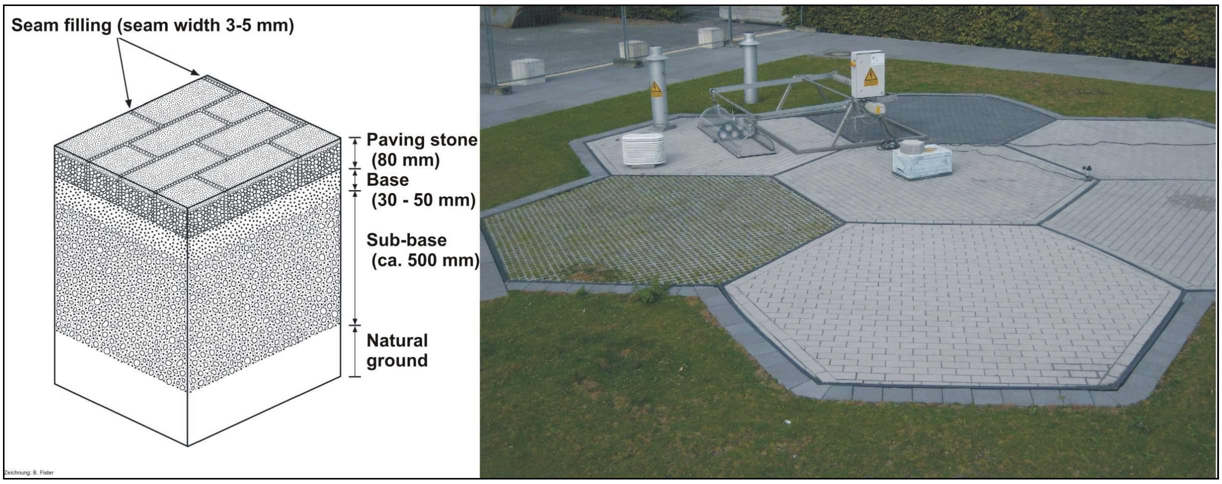

Figure 1: Left side: Block diagram of a WPP constructed according to approved national technical specification; Right side: Testfield in Coesfeld, Germany with central reference area (Area 2.1- see block diagram) and differing outer areas

Nearly all pavements consist of the paving stone with a seam filling directly at the surface, below which is a base and a sub-base laid on the natural ground (Figure 1, left side). The main focus of the research was on the impacts of different sub-base materials on the evaporation rates. Therefore, Area 2.2 was designed with a twin-layer sub-base, as is often used in Dutch pavement-construction. The materials used are shown in Table 1. The Dutch sub-base is characterised by a coarse grained upper layer with a high proportion of fine grains. The second sub-base below is made of special drainage sand. In German regulations (TL SoB 2004), there is a specific range of acceptable grain size distribution of the sub-base (and also for other layers). That is necessary because different grain size distributions change some physical and, in most cases, all hydraulic attributes of the layer. Therefore, one aim of this research was to exhaust this range and to built one test area with an "as fine-grained as possible" and one area with an "as coarse-grained as possible" sub-base. For this, the exact grading curves (TL SoB 2004) were mixed and after passing through the laboratory tests, the materials were built in Area 2.4 (i.e. fine grained sub-base) and in Area 2.5 (i.e. coarse-grained sub-base).

Included in the street design, that accords with the national technical approval system, are four variations of sub-base in the test field. In addition to the influence of the sub-base on the evaporation rates, some variations of the upper surface were built in. The simplest variation is a change in colour. Therefore, Area 2.3 is paved with anthracite paving stones made of the same pervious concrete and with the same shape as on Area 2.1.

On parking lots and courtyard entrances, the prevalent kind of WPPs are grass pavers. The comparison between Area 2.1 and Area 2.7 (grass paver) allows an assessment of the transpiration effect of the grass on the evaporation rates. The last area (Area 2.6) with an impermeable paving stone is described in Starke et al. (2009). All general information on the materials used is shown in Table1.

	Properties	**Area 2.1** Reference area	**Area 2.2** Sub-base netherlands	**Area 2.3** Paving stone colour	**Area 2.4** Sub-base fine	**Area 2.5** Sub-base coarse	**Area 2.7** Grass paver
Paving stone	Material	pervious concrete paver					grass paver (pervious concrete)
	Colour	grey	grey	antracite	grey	grey	brown
	Size	200·100·80 mm	200·100·80 mm	200·100·80 mm	200·100·80 mm	200·100·80 mm	250·250·80 mm
Seam	Material	1/3 basalt chippings	1/3 basalt chippings	1/3 basalt chippings	1/3 basalt chippings	1/3 basalt chippings	1/3 basalt chippings/extensive substrata 30/70%
	Width	3-5 mm	3-5 mm	3-5 mm	3-5 mm	3-5 mm	ca. 48·48 mm
Base	Material	2/5 hard limestone	2/5 hard limestone	2/5 hard limestone	2/5 hard limestone	2/5 hard limestone	1/3 basalt chippings/extensive substrata 70/30%
	Thickness	30-50 mm	30-50 mm	30-50 mm	30-50 mm	30-50 mm	30-50 mm
Sub-base	Material	0/32 hard limestone	1. 0/45 grey wacke 2. 1/3 sand	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone	0/32 hard limestone
	Thickness	500 mm	1. 250 mm 2. 250 mm	500 mm	500 mm	500 mm	500 mm
Total Pavement	Part of seams	5.9 %	5.9 %	5.9 %	5.9 %	5.9 %	ca. 55.3%
	Age	new installed					
	Gradient	0%					
		No disturbances from the sourrounding					

Table 1: Characteristics of the test-fields areas

To compare the evaporation rates of pavements with different street layers, the outer areas differ from Area 2.1 in the centre. By a Tunnel-evaporation gauge (TUV), further described in Werner (2000), Weiß et al. (2002) and Starke et al. (2009), the hourly evaporation rates are measured with a time resolution of 12 minutes (five measurements per hour). The TUV is placed between the two compared areas and the tunnel measuring-unit is pivoted by a lifting arm alternately on both pavement surfaces. In addition to the TUV, a Hellman rain gauge allows a precipitation-evaporation correlation. The near-surface air temperature and the relative air humidity were measured by the integrated sensors of the TUVs.

The test period was from August 2008 to October 2009. Pre-examinations by Göbel et al. (2008) show that evaporation rates from WPPs are heavily dependent on the weather. Due to the fact that there is only one TUV, but six possibilities to compare pavements, a continuous measurement over the whole year was not possible for all areas simultaneous. To get a comparison between all pavements surfaces, there should be identical weather conditions at every measurement. In a field test this is not possible and therefore the analysis of the measured evaporation rates will just be based on similar weather conditions.

3. RESULTS

The laboratory tests show that, especially, the fine-grained materials are not suitable for water-permeable street building. The biggest criterion of exclusion was that of water permeability. The results for the different materials used in the test field are shown in Table 2. For evaporation the most relevant parameters of hydraulic conductivity, water retention and capillary rise are shown. Additionally the Proctor-density, the status of the material in the field test is shown. For the sub-base, there are some more parameters in the table, like the Flakiness- and the Shape-Index. Both parameters are important for the stability of the pavement but their influence on evaporation rates has not been researched yet.

	Properties	Unit	DIN EN-standard	**Area 2.1** Reference area	**Area 2.2** Sub-base netherlands	**Area 2.3** Paving stone colour	**Area 2.4** Sub-base fine	**Area 2.5** Sub-base coarse	**Area 2.7** Grass paver
Paving stone	k_f	m/s	18130-1:1998	$8.1\cdot10^{-4}$	$8.1\cdot10^{-4}$	$1.3\cdot10^{-4}$	$8.1\cdot10^{-4}$	$8.1\cdot10^{-4}$	n.m.
	$wrc_{mat.}$	Vol.-%	1097-6:2000	7.5	7.5	7.8	7.5	7.5	7.5
	$wrc_{pav.}$	l/m^2	n.a.	5.7	5.7	5.9	5.7	5.7	3.6
Seam	k_f	m/s	18130-1:1998	$3.3\cdot10^{-3}$	$3.3\cdot10^{-3}$				-
	$wrc_{mat.}$	Vol.-%	1097-6:2000	10.6	10.6				20.9
	$wrc_{pav.}$	l/m^2	n.a.	0.5	0.5				9.2
	ρ_w	g/cm^3	13286-2:2004	1.62	1.62				1.45
	$h_{cr.}$	m	1097-10:2003	0.13	0.13				0.35
Base	k_f	m/s	18130-1:1998	$4.2\cdot10^{-2}$	$4.2\cdot10^{-2}$				$4.3\cdot10^{-5}$
	$wrc_{mat.}$	Vol.-%	1097-6:2000	4.1	4.1				20.1
	$wrc_{pav.}$	l/m^2	n.a.	1.6	1.6				7.8
	ρ_w	g/cm^3	13286-2:2004	1.64	1.64				1.53
	$h_{cr.}$	m	1097-10:2003	0.08	0.08				0.33
Sub-base	k_f	m/s	18130-1:1998	$9.0\cdot10^{-4}$	1. $< 10^{-9}$ 2. $4.4\cdot10^{-5}$	$9.0\cdot10^{-4}$	$5.7\cdot10^{-5}$	$4.2\cdot10^{-5}$	$9.0\cdot10^{-4}$
	$wrc_{mat.}$	Vol.-%	1097-6:2000	4.4	1. 10.5 2. 22.3	4.4	11.5	11.9	4.4
	$wrc_{pav.}$	l/m^2	n.a.	22.0	1. 26.5 2. 55.8	22.0	57.5	59.5	22.0
	ρ_w	g/cm^3	13286-2:2004	2.13	1. 2.23 2. 1.35	2.13	2.24	2.13	2.13
	FI	1	933-3:1997	FI 27	1. FI 29	FI 27	FI 30	FI 28	FI 27
	SI	1	933-4:1999	SI 17	1. SI 16	SI 17	SI 16	SI 16	SI 17
	$h_{cr.}$	m	1097-10:2003	0.10	1. 0.37 2. 0.47	0.10	0.33	0.33	0.10
Total Pavemen	k_f	m/s	18130-1:1998	$3.5\cdot10^{-3}$	$3.4\cdot10^{-3}$	$3.3\cdot10^{-3}$	$3.6\cdot10^{-3}$	$3.6\cdot10^{-3}$	$2.8\cdot10^{-3}$
	$wrc_{mat.}$	Vol.-%	1097-6:2000	4.8					
	$wrc_{pav.}$	l/m^2	n.a.	29.8	90.1	30.0	65.3	67.3	42.6

Minimum requirements: k_f: $5.4\cdot10^{-4}$; *SI*: max. 50; *FI*: max. 50; n.a. = not available; n.m. = not measurable

Table 2: Methods and results of the laboratory tests for the materials used

Table 2 shows that the base and the seams present a zone of high permeability in the pavement. In all areas, the sub-base has a 2 orders of magnitude lower permeability and in Area 2.5 it is even less permeable than required ($k_f \geq 5.4*10^{-4}$ m/s). Its use in normal pavements is, strictly speaking, not possible. However, in water-permeable street building it is not common to test every single material, just the total pavement. This is the only acceptance-criterion in water permeability. The permeability of the whole pavement of Area 2.5 is clearly higher than needed. Therefore, the material is used further and is described as being suitable for WPPs. The same situation on Area 2.2: The upper sub-base is even completely impermeable in the laboratory test, but the total pavement shows an adequate permeability.

The $wrc_{mat.}$ values of the paving stones are almost equal on all surfaces (7.5-7.8 Vol.-%), an exception being Area 2.7. Here, the $wrc_{mat.}$ is equal to the other surfaces, but the value of the pervious surface concrete is lower ($wrc_{pav.}$ 3.6 l/m^2 to 5.7-5.9 l/m^2). The surface consist of 55.3% seams, so there is more seam-surface than paving stone-surface. In contrast with the other areas, the seam-filling plays a decisive role. With 12.8 l/m^2, the $wrc_{.pav.}$ of the seam-filling and the paving stone is at least twice as high as on the other areas. In the sub-bases, Area 2.4 and Area 2.5 show a high $wrc_{mat.}$ and $wrc_{pav.}$. and both values are nearly threefold those of the *wrc* values for Areas 2.1, 2.3 and 2.7. The highest *wrc* was in the sub-base of Area 2.2. The bottom sub-base can retain 22.3 l/m^2 water.

The bases of all paved areas show low capillary rise (8 cm), whereas the base material of Area 2.7 can raise the water head up to 33 cm against gravity. Capillary effects from the natural underground are just prevented by the sub-base.

In Figure 2, a typical comparison of evaporation measurements is shown. In this case, Area 2.1 and Area 2.3 are compared. The red and green lines, reflecting the evaporation rates, show the typical daily curve. In relation to the precipitation events (blue bars) the interconnections between rain events and evaporation can be seen. The highlighted periods (coloured boxes) are the same periods described in Table 3; blue is for a rainy period, orange for a drying period and red for a dry period. In Figure 2 there are, all in all, 3 measuring periods (26.09.08 - 05.10.08; 08.06.09 -14.06.09 and 06.10.09 – 20.10.09). Therefore, the evaporation rates are differently high. In June, the evaporation rates are much higher than in October. Obviously, the red line (Area 2.3) shows at noon a higher evaporation rate than in Area 2.1. At night, the evaporation rates are insignificant and have just little influence on the total evaporation.

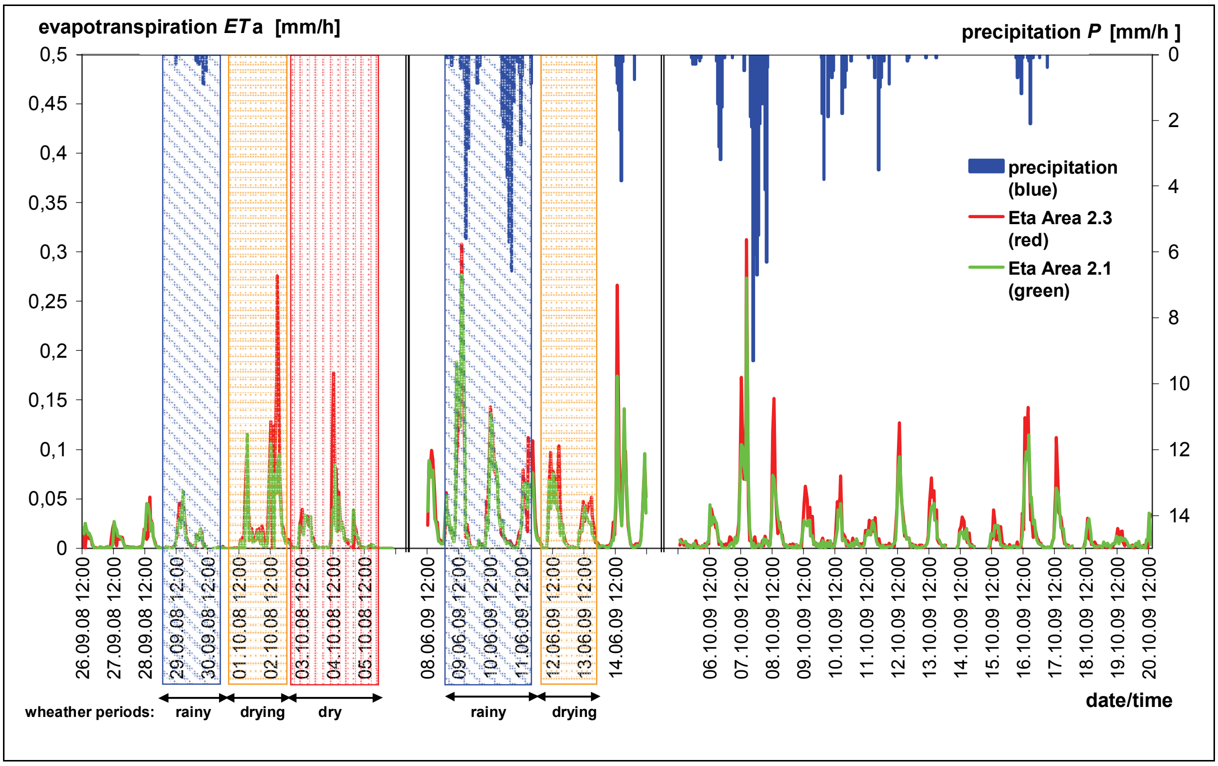

Figure 1: Results of the meteorological measurement for Area 2.3 and 2.1, Discussed weather periods of Table 3 are highlighted

The results of the meteorological measurements are summarized in Table 3. Because of the large amount of measurements (over 4.5 million single values of the different parameters) the results are only summarized in this paper.

Changing weather conditions make it is necessary to focus on three special weather periods: “rainy days” (days with rain events), “drying days” (the two dry days following a rainy day) and “dry days” (at least two dry days between this period and the last rain event). These periods are taken for every compared area.

All three weather conditions of every area are taken for a warm period (average temperature > 18 °C) and a cold period (average temperature ≤ 15 °C). Because of insignificant evaporation rates at night, all values in Table 3 were measured between 8am and 8pm. In the course of the project, there are longer and more periods measured, so the data pool is much bigger and covers nearly all weather conditions available. For the two parameters temperature ϑ and actual evaporation Et_a, there is always the minimum, the average and the maximum value of a period given. The relative air humidity *rF* is shown on average for the according period. In the text, *rF* and ϑ are not discussed further, but for the sake of completeness and for a better reconstruction of the results, both values are shown in Table 3. In addition, the cumulated evaporation rates Et_{cum} are compared relatively to the evaporation rates of Area 2.1. This is essential for the same measuring period and in the comparison the Et_{cum} of Area 2.1 always equates to 100 %. There is only one exception in the warm period, where Areas 2.4 and 2.5 were compared directly. This results from insignificant evaporation-differences between the “normally grained” sub-base of Area 2.1 and both other areas. To get bigger differences in evaporation, the fine-grained and the coarse-grained sub-bases were compared directly.

			Warm days			Cold days		
			Rainy	Drying	Dry	Rainy	Drying	Dry
Area 2.1	Measuring period	date	27.05.08-29.05.08	29.05.09-30.05.09	19.09.08-21.09.08	14.11.09-16.11.09	23.10.09-24.10.09	18.03.09-20.03.09
	Average *J*	°C	19.40	24.2	17.5	9.2	12.0	11.0
	Min./max. *J*	°C	12.8/28.1	16.5/29.6	7.5/26.4	5.5/11.7	8.2/17.4	3.0/19.3
	Average *rF*	%	53.3	35.0	53.6	92.1	82.2	49.0
	Average Et_a	mm/h	0.057	0.014	0.005	0.003	0.013	0.005
	Min/max Et_a	mm/h	0.013/0.147	0.005/0.04	0/0.181	0/0.023	0/0.032	0/0.014
Area 2.2	Measuring period	date	27.05.08-29.05.08	29.05.09-30.05.09	19.09.08-21.09.08		In measuring	
	Average *J*	°C	19.40	24.2	17.5			
	Min./max. *J*	°C	12.8/28.1	16.5/29.6	7.5/26.4			
	Average *rF*	%	53.3	35.0	53.6			
	Average Et_a	mm/h	0.037	0.019	0.006			
	Min/max Et_a	mm/h	0/0.087	0.012/0.034	0/0.189			
	Et_{cum} % of area 2.1	%	65.2	73.2	108.4			
Area 2.3	Measuring period	date	09.06.09-11.06.09	12.06-13.06	04.08.09-06.08.09	29.09.08-30.09.08	01.10.08-02.10.08	03.10.08-05.10.08
	Average *J*	°C	18.2	22.6	32.1	12.7	12.0	10.7
	Min./max. *J*	°C	12.0/26.6	14.3/29.5	20.1/39.8	9.3/18.4	8.2/17.4	5.4/15.4
	Average *rF*	%	72.2	38.4	31.4	85.6	82.2	74.8
	Average Et_a	mm/h	0.046	0.046	0.021	0.013	0.061	0.025
	Min/max Et_a	mm/h	0/0.307	0.006/0.104	0.026/0.045	0/0.05	0/0.275	0/0.178
	Et_{cum} % of area 2.1	%	101.7	144.8	-	117.1	158.4	159.4
Area 2.4	Measuring period	date	20.06.09-21.06.09	22.06.09-23.06.09	24.06.09-26.06.09	14.03.09-15.03.09	16.03.09-17.03.09	18.03.09-20.03.09
	Average *J*	°C	19.6	23.7	24.1	6.3	9.5	11.0
	Min./max. *J*	°C	13.7/27.1	13.7/27.1	15.5/34.0	4.9/8.0	2.9/18.7	3.0/19.3
	Average *rF*	%	56.6	46.3	52.9	90.7	57.2	49.0
	Average Et_a	mm/h	0.058	0.019	0.018	0.008	0.012	0.009
	Min/max Et_a	mm/h	0.006/0.184	0.004/0.036	0.001/0.035	0/0.021	0/0.046	0/0.033
	Et_{cum} % of area 2.1	%	117.3 % of $Et_{cum\ area2.5}$	76.5 % of $Et_{cum\ area2.5}$	112.9 % of $Et_{cum\ area2.5}$	76.1	130.6	161.1
Area 2.5	Measuring period	date	20.06.09-21.06.09	22.06.09-23.06.09	24.06.09-26.06.09	26.10.09	23.10.09-24.10.09	21.10.09
	Average *J*	°C	19.6	23.7	24.1	12.1	13.0	12.7
	Min./max. *J*	°C	13.7/27.1	13.7/27.1	15.5/34.0	11.2/13.1	7.1/22.0	5.9/19.1
	Average *rF*	%	56.6	46.3	52.9	89.7	73.0	54.8
	Average Et_a	mm/h	0.049	0.025	0.016	0.011	0.01	0.01
	Min/max Et_a	mm/h	0.009/0.183	0.004/0.049	0/0.033	0.002/0.025	0/0.027	0.001/0.037
	Et_{cum} % of area 2.1	%	directly compared to area 2.4 (see above)			82.8	80.2	172.4
Area 2.7	Measuring period	date	12.09.08	13.09.08-14.09.08	15.09.08		In measuring	
	Average *J*	°C	18.0	17.7	15.2			
	Min./max. *J*	°C	14.9/21.8	8.9/23.5	10.0/20.4			
	Average *rF*	%	87.0	56.2	58.5			
	Average Et_a	mm/h	0.018	0.043	0.024			
	Min/max Et_a	mm/h	0.003/0.032	0/0.168	0/0.083			
	Et_{cum} % of area 2.1	%	155.5	290.9	261.3			
	Days from 8 AM to 8 PM (MESZ); Warm days with average *T* >18°C; Cold days with *T* < 15°C							

Table 3: Summarized meteorological measurements focussed on selected weather conditions

In regard to the weather during the project, it was not possible to get results for all six weather conditions in all areas and the cold weather conditions, in particular, have gaps. These missing periods will be measured in a future project.

4. DISCUSSION

Area 2.2

The laboratory tests show that the fine-grained twin-layer sub-base is not suited for German street building and, in particular, the drainage-sand is insufficiently permeable. The use of sand in street building further creates problems in terms of the stability of the pavement. A realized compression test, in compliance with TP BF-StB part B 8.3 (2003), shows, that the achieved stability of 72.0 MN/m^2 is less than the required 120 MN/m^2. This pavement cannot resist the demands of traffic and is more suitable for cycle lanes and footpaths and a large-scale use, as with the construction method of Area 2.1, is not possible.

The evaporation rates are on average (all measurements) 16 % lower than on Area 2.1. It is only in dry periods that this road structure has an 8.4 % higher evaporation rate. In the rainy and drying periods, the evaporation rates are 34.8 % respectively 26.7 % lower than on the reference area. Measurements in cold weather have not been not realised yet.

The results lead to the supposition that a more fine-grained sub-base decreases the evaporation rates. If this supposition is right, the evaporation rates of Areas 2.4 and 2.5 will show equal results with lower/higher evaporation rates as on Area 2.4 and Area 2.5. If these effects will be not observed, this effect could result from the twin-layer sub-base.

Area 2.3

Except for the paving stone, all sub-surface layers in Area 2.3 are the same as in Area 2.1. The *wrc*$_{\text{mat.}}$ of the paving stone is a 4 % higher than the grey paving stone in Area 2.1. Therefore, the amount of available water for evaporation may be a bit higher (3.5 %). The difference in the wrc$_{\text{mat.}}$ can increase the evaporation rates. The albedo of the dark anthracite paving stone is lower than in the grey one what results in higher energy absorption from sunlight. Therefore, the energy, available for evaporation, is higher. In consequence, the evaporation is, in all weather conditions, higher than in Area 2.1. The effect increases from wet to dry weather conditions and, on average, the evaporation in Area 2.3 is 19% higher than in Area 2.1. This is much more than the 3.5 % more water that is retained in the anthracite paving stone. This leads to the conclusion that, in addition to the water, the limiting factor for evaporation in Area 2.1 is the energy input. Although the energy input (from solar radiation) on both areas was the same during the measurement period, the higher absorption rate of the anthracite paving stone (with lower albedo) leads to more available energy for evaporation. The available energy for evaporation is not just influenced by the albedo as the energy must reach the stored water in the pores of the paving stone. When the surface is dry, the heat conductivity of the paving stone influences the evaporation rates. In a further project, the impacts of higher and lower heat conductivity characteristics will be observed.

Area 2.4

The sub-base is suitable for water-permeable street building and it is characterized by a high *wrc* and a $h_{\text{cr.}}$ of 0.33 cm. So there is a large amount of water that is kept in this layer and further water may be raised from the natural ground. The base (the same in Areas 2.1, 2.2, 2.3 and 2.5) is anti-capillary. Therefore, there is no direct water flow from the sub-base to the surface and the upward water movement can only happen by gas and vapour transport. If there is an influence on evaporation rates, the amount of vapour transport may be a limiting factor. On cold days the evaporation measurements show that the evaporation compared to Area 2.1 is lower during rainy periods and higher in dry periods. To have more significant variances in the sub-base, the evaporation rates of the warm period were compared with Area 2.5. The results show variances based on the weather conditions. In rainy and dry periods, the fine-grained sub-base seems to increase the evaporation rates. In drying days, the coarse-grained sub-base benefits the evaporation rate. A significant trend over the whole project was not observed. The cumulated evaporation rates of Area 2.4 and Area 2.5 differ by just 0.1 %.

Area 2.5

Because of the permeability of the whole pavement (k_{f} = $3.6 \cdot 10^{-3}$ m/s), the sub-base material is suitable for WPPs. Similar to Area 2.4 the *wrc* and the h_{cr} is higher than in Area 2.1, but the base prevents a capillary rise to the surface. Area 2.5 was compared with Area 2.1 and with Area 2.4 (see above). The results for Area 2.2, namely that the lower evaporation rates are caused by the more fine-grained sub-base, cannot be verified. The decreased evaporation rates of Area 2.2 seem to result from the twin-layer sub-base. Therefore the effect of twin-layers will be considered in a further project.

Area 2.7

The whole street design is only suitable for courtyard entrances and parking lots and so the field of application is not broad. In spite of this, the transpiration effect of the grass far exceeds the evaporation of the pervious concrete paver. In fact, an overgrown area of approximately 55 % (part of the seams) increases the evaporation nearly threefold. During the whole project, the evaporation rates were about 243 % higher than in Area 2.1. These measurements represent only the difference for summer conditions: during the winter, the transpiration of the grass will decrease and the evaporation rates will attenuate to the ones of Area 2.1. Any effects of the seam-filling and the grid-like paver made of porous concrete are superimposed by the evapotranspiration of the grass. The high *wrc* of the seam and the big part of the seams may benefit the evaporation further. These effects may be more visible in the winter results of a further project.

5. CONCLUSIONS

The direct inter-connection between all data measurements is actually not possible and at the moment it is only possible to compare the reference central area with one outer area. In spite of this, it is possible to see trends and draw conclusions of the actual measurements.

The results of the measurements show that evaporation rates from WPPs can be affected by the sub-base. The test area with the fine-grained and twin-layer sub-base of the typical Dutch street body shows 16 % lower evaporation rates than that for the street body according to the German national technical approved quality. The further areas with the fine-grained and coarse-grained materials with the limits of the German street building regulations show no effect (0.1 %). Bigger variations in the grain size distribution are not permissible in Germany and, therefore, an evaporation optimization through a change in the sub-base is not practicable. The effect of twin-layers will be further investigated.

The anthracite paving stone shows a 19 % higher evaporation than the grey one. This simple change in the albedo, and the increase of energy absorption at the paving stone surface, initiates the evaporation earlier and leads to higher evaporation following rain events. This rain-evaporation interconnection is still lower than on impermeable pavements, so sultriness after rain events produced by these paving stones is not expected.

The results of the grass paver area show that it is not possible to increase the evaporation rates of the pervious concrete paver on one level with the evaporation rates of overgrown surfaces, like the grass paver (243 % higher than the reference area). But with the possibility of using the pervious concrete pavers on a large scale, even small increase of evaporation rates, would have a positive effect on the urban climate. The paving stone is directly exposed to the sun energy and therefore the biggest potential of an evaporation optimization is in the paving stone itself. Further, the seam-filling may be very important because, although there is no high $wrc_{pav.}$ in the seam filling, the seam may act like a connector to the deeper layers. By gas and vapour transport, the water of deeper layers may affect the evaporation rate.

In a further project, the pavements of the test field will be removed, except in Area 2.1. All outer areas will be built up with equal sub-base and base. Variations will only exist in the paving stone and the seams. Therefore, some prototypes of new water-permeable paving stones are under development. These prototypes will be again tested in the laboratory. Alongside the described tests, the heat-conductivity will also be tested.

In consequence, the result of this project will allow the implementation of a regional-specific adjustment in different street building materials so as to influence the water-balance and the urban climate.

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