FINAL DRAFT

Novo, A.V., Bayon, J.R., Castro-Fresno, D., Rodriguez-Hernandez, J. (2013) Monitoring and evaluation of the thermal behavior of permeable pavements for energy recovery purposes in an experimental parking lot: Preliminary results. Journal of Energy Engineering, 139 (3), pp. 230-237. http://ascelibrary.org/doi/abs/10.1061/(ASCE)EY.1943-7897.0000106

Monitoring and evaluation of the thermal behaviour of permeable pavements for energy recovery purposes in an experimental parking lot: Preliminary results

Amaya V. Novo[1]; Joseba R. Bayon[2]; Daniel Castro-Fresno[3]; and Jorge Rodriguez-Hernandez[4]

Abstract: Permeable pavements offer a solution for rainwater runoff treatment in urban areas, combining water management with water reuse purposes when the sealed sub-base become rainwater reservoirs. Furthermore, the thermal behaviour investigations of these systems have proved their contribution to palliate the urban heat island effect in the hottest season and to delay freezing during the coldest season. Increasing knowledge of heat transfer mechanisms into the permeable pavements and their sub-base has enabled the use of these structures combined with Ground Source Heat Pumps (GSHP) in addition to the other well-known applications. The aim of the present study is to investigate the thermal response observations of permeable pavements under specific

[1] Department of Transport and Technology of Projects and Processes, School of Civil Engineering (E.T.S.I.C.C.P.), University of Cantabria, 39005 Santander, Spain (corresponding author). E-mail: amavega@yahoo.es (A.V. Novo).
[2] Department of Transport and Technology of Projects and Processes, School of Civil Engineering (E.T.S.I.C.C.P.), University of Cantabria, 39005 Santander, Spain.
[3] Department of Transport and Technology of Projects and Processes, School of Civil Engineering (E.T.S.I.C.C.P.), University of Cantabria, 39005 Santander, Spain.
[4] Department of Transport and Technology of Projects and Processes, School of Civil Engineering (E.T.S.I.C.C.P.), University of Cantabria, 39005 Santander, Spain.

weather conditions while paying attention to the temperature distribution in the sub-base, where rainfall water is stored for others uses, in order to evaluate the possibility of introducing GSHP technology. The bedding layer and sub-base temperature of reinforced grass permeable pavements was monitored during 3 months in summer 2008 and the preliminary results obtained show sub-base temperature different from the air temperature during the period of study; and demonstrate that the sub-base is less affected by the air temperature than the bedding layer due to the insulating capacity of permeable pavements, explained through the heat transfer processes that take place into the pavements.

Subject headings: Permeable pavement; Heat transfer; Water reuse; Ground Source Heat Pumps (GSHP).

1. Introduction

Global energy consumption is increasing and countries throughout the world are stimulating research in renewable energies in order to face the future energy challenges (Wang and Tseng, 2012). In this sense, energy efficiency (EE) policies are implemented in developed and developing countries, stimulating the development of new technologies and applications (Norero and Sauma, 2012), for instance permeable pavements combined with ground source heat pump (GSHP) technologies.

Permeable pavements in parking lots combine storm water retention systems with pollutant removal and groundwater recharge (Pratt 1999). Permeable pavements are also capable of reducing the heat island effect by means of evaporative cooling; since porous layers retain a significant amount of water, which is released back into the atmosphere through evaporation during sunlight hours (Wanphen and Nagano 2009).

Besides, this type of Sustainable Urban Drainage Systems (SUDS) could be used as an energy storage device as part of a geothermal energy system (Scholz and Grabowiecki 2007; Tota-Maharaj *et al*. 2009).

Researchers at the University of Coventry are beginning to develop systems for the use of rainwater stored in the sub-base of permeable pavements, providing SUDS that integrate these water reservoirs with GSHP technologies. This is accomplished by introducing heat exchangers at the bottom of the sub-base to recover and deposit the heat in a similar way to geothermal systems. The heat is moved via heat pump for domestic heating and cooling (Coupe *et al.* 2009). GSHP technologies are widely introduced in some countries in order to comply with reduction of green house gas (GHG) emissions and renewable energy source use policies (Sanner *et al.* 2003).

Heat transfer through permeable pavements involves convection and radiation in the pores, and conduction in the solid aggregates (del Coz Diaz *et al*. 2009). The heat flows from points of higher temperature to cooler zones, which is demonstrated through the temperatures distribution into the soils (Hermansson *et al.* 2009). Several studies have developed models based on energy balance in pavements, which include heat transfer by convection, conduction, radiation and vapour diffusion (Gui *et al.* 2007; Hermansson 2004; Van Buren *et al*. 2000; Wanphen and Nagano 2009). Solar and infrared radiation, wind speed and air temperature are climatic factors of great importance in the surface temperatures of pavements, as are rain events and evaporation. Observations of the temperature in pervious concrete pavements have shown how surface temperatures are higher than the air temperature due to solar radiation absorption while temperature fluctuation inside the pavement decreases with depth due to the insulating capacity of the air mass in the pervious pavement and aggregate bedding layer (Kevern *et al.* 2009).

The temperature within a permeable pavement is strongly influenced by the air temperature; temperature changes on the surface induce heat flow in the pavements. However, the air produces a more significant insulating effect than the one observed in impervious pavements (Bäckström 2000). Part of the solar radiation is employed in evaporating the water retained in the porous material, which explains the lower temperatures obtained in permeable pavements surfaces. Hence, the porosity provides insulating abilities to soils (thermal conductivity of the pavement decreases with increasing porosity), but water saturation of pores increases the ground's thermal conductivity (Zhang *et al.* 2007). However, permeable materials with large void sizes can drain more easily to deeper layers so less water is kept near the surface available for being evaporate so the cooling effect of evaporation is reduced, which implies that the pavement warms like an impervious pavement (Asaeda and Ca 2000).

The main objective of this study is to evaluate the feasibility of GSHP in the sub-base, composed of aggregates and water, under reinforced grass permeable pavements.

2. Materials and methods

2.1. Study location

The University of Cantabria is involved in the design, construction and monitoring of a unique experimental pervious parking area in Santander, Spain. Average daily maximum temperatures vary from 25°C in summer to 13°C in winter; total annual precipitation is up to 1100mm.

Different types of pervious pavements have been constructed, in order to study quantity and quality aspects of water simultaneously (Gomez-Ullate 2010). The experimental parking lot has been monitored since 2008 and temperature sensors were installed during construction to evaluate the long term thermal response within the pavements.

The experimental parking lot of Las Llamas consists of 45 parking bays built of different types of permeable pavements: concrete block, porous asphalt, porous concrete, reinforced grass with concrete grid and reinforced grass with plastic grid. Permeable pavements allow the water to drain through the pavement and the bedding layer into the aggregate sub-base where the water is stored. There is a geotextile installed in most of the parking bays between the bedding layer and the sub-base in order to prevent fine particles passing and clogging the voids. The common structure is formed with a 35cm sub-base of limestone aggregate and has voids ranging from 33% to 35 %; moreover the bedding layer is formed of limestone gravel.

The surface areas of each parking bay are 4.2 x 2.4m. The characteristics of the permeable pavement types thermally monitored in this preliminary study are shown in Table 1 and the thermal properties of pavement materials are showed in Table 2.

2.2. Methods

The measurement instruments are temperature probes Pt100 (accuracy ±0.13ºC at 20ºC) and a MadgeTech® OctRDT datalogger (accuracy ±0.1ºC). The air temperature, wind velocity and precipitation are recorded with a meteorological station located at a height of 12m on a lamppost in the parking lot. Solar radiation datas have been provided by the State Meteorological Agency (AEMET).

Initially, 3 parking bays of the parking lot numbered 39, 43 and 44 respectively were monitored during 3 months. Pavement surface temperatures are not measured because the investigation is focused on the sub-base temperature behaviour during the period of study.

The location of the parking bays is shown in Figure 1, all of them are surrounded by two others on each side. Their typologies are reinforced grass with concrete grid and reinforced grass with plastic grid (Figure 2).

There are two tubes horizontally placed in order to introduce the temperature probes and protect them from the granular material. One sensor is located at 15cm depth, just above the geotextile, and the other sensor is situated at 50cm depth, at the bottom of the sub-base; as is showed in the scheme in Figure 3.

Each parking bay in the experimental parking lot has a manhole for different measurement instruments. In one of them, the datalogger has been installed within a watertight box to protect it from getting wet, and connect it with 6 temperature probes corresponding to parking bays 39, 43 and 44. The temperature sensors were conducted by pairs to the measurement devices at the corner of each parking bay through corrugated tubes placed inside the permeable pavement (Figure 4). Temperature measurements were taken every 30 minutes for 3 months, as well the meteorological variables.

3. Results

3.1. Temperature response

The pavement temperatures depend greatly on the weather, normally changing every hour and from day to day. However, some differences can be appreciated during the measurement period. The graphs show strong daily temperature oscillations in the sensors measurements at 15cm depth and less appreciable oscillations in the sensors measurements at 50cm, corresponding to the sub-base (Figure 5, Figure 6 and Figure 7). The air temperature is cooler most of the days than the permeable pavement bedding layer and sub-base temperatures; but the sub-base layer temperature daily variations are much less notable.

These phenomenons could be explained by means of heat transfer mechanisms produced inside the pavement. For pavements, conduction is the most important factor for heat transfer; thermal conductivity decreases with increasing porosity and increases with increasing degree of water saturation (Zhang *et al.* 2007). During warm and sunny days the pavement surface temperature undergoes strong daily oscillations and in pavements materials with a high thermal diffusivity this oscillation penetrates to greater depths and the temperature of the pavement bedding layer may reach high values. The heat is transferred basically by conduction inside the pavement although convection takes places in the porous layers as well. Therefore, sunlight absorption causes the maximum pavement temperature to be significantly higher than the surrounding air temperature in the 15cm depth sensor. At 15cm, maximum daily high temperatures are observed between 6 – 9 pm while maximum daily high air temperatures are observed between 3 – 6 pm or even before. This fact indicates different heat transfer rates in deeper layers then, different thermal properties (see Figure 8 and Figure 9). After the maximum temperatures registered, the heat stored in the pavement is conducted from the pavement material to the surface and, finally, to the air.

At twilight, when the solar radiation diminishes, the surface emits heat to the atmosphere by convection and radiation which implies an air temperature increment in urban areas, well-known as the urban heat island effect. The cooling process due to the temperature difference between air and pavement surface is delayed in deeper layers which have a porous structure that provides permeable pavement and aggregate bedding layer with insulating capacity. The thermal conductivity of the permeable pavement diminishes due to the evaporation occurred when water is retained in the pores for capillarity or previous rain events, and solar radiation reaches the pavement surfaces.

The evaporation phenomenon in permeable pavements has been researched in a previous investigation in this experimental parking lot (Gomez-Ullate 2010). Water level measurements (accuracy ±1 mm) through an external tube connected to the bottom of the sub-base in each parking bay, revealed that the water stored in the sub-base was around their maximum capacity during the period of October 2008 to October 2009; being the temperature the climatic factor more highly correlated with the stored water levels. Pavements constructed with geotextile, like the ones presented in this study, showed evaporation only during the dry period, even though not significant water level differences were found. Consequently, evaporation in permeable pavements should be considered in the future GSHP application as a heat transfer mechanisms related to the evaporation of water retained in the porous materials instead of the stored water levels of the sub-bases.

At the end of the studied period, the differences between air temperature and the pavement temperatures registered were not so pronounced, becoming closer in the last month. Moreover, the sub-base keeps greater temperatures than the bedding layer and air temperatures at the end of the period of study. As for the sub-base temperatures obtained, heat transfer through the pavement and the insulating ability of the porous pavement and the bedding layer produce a buffered temperature response with increasing depth, as it is shown in Figure 10 where the daily mean temperatures of the permeable pavements at both depths and the daily mean air temperatures are represented.

3.2. Statistical data analysis

The statistical software program SPSS® version 17 was used for the statistical analysis. The temperature measurements were not normally distributed and the Friedman's test indicates that there are significant differences in temperature measurements at 15cm, temperature measurements at 50cm and air temperature values for the three parking bays; $p<0.05$ was assumed as a significant statistical value. So there is a different thermal response between the bedding layer, sub-base and air temperatures. The shallow bedding layer (15cm) and sub-base (50cm) mean temperatures are at least 2.5ºC higher than the air temperature and the maximum sub-base temperature reached 24.28°C during the period of study (Table 3).

The Wilcoxon signed-rank test was applied for pairwise comparison of temperature data obtained from the sensor 1 and sensor 2. The analysis shows significant differences between each pair of related samples, which includes the temperatures measurements at two depths for each parking bay so that the thermal response of the bedding layer at 15cm depth (sensor 1) and sub-base at 50cm (sensor 2) depth are significantly different between them.

Finally, a non-parametric test is performed to describe the relationship between two ordinal variables, temperature measurements and each ambient variable. The relationships between temperatures registered in each parking bay at two different depths and the climate variables are summarized by Spearman's rank correlation coefficients in Table 4. Results of the statistical analysis show the influence of local weather factors on the thermal behaviour of the reinforced grass pervious pavements.

Air temperature and pavement temperatures measured at 15cm depth were significantly correlated, as for the temperatures measured in the sub-base, at 50cm depth, with lower Spearman's rho coefficients ($p<0.01$). These results suggest that ambient temperature affects pavement temperatures in some way; the influence at 15cm depth is slightly greater than the strength of association estimated for the sub-base temperature at 50cm depth.

There is a certain inverse relationship between pavement temperatures at both depths and rain, reflected in the correlation coefficients for the rain and the temperatures measured at 15cm and 50cm depth ($p<0.01$). Wind speed is positively correlated with the bedding layer temperatures, however it was expected to be negatively correlated as this factor is thought to be related to cooling process. This fact may be explained by greater evaporation occurring in the permeable pavement voids, so that water is replaced by air. This increases the insulating capacity of the pavement, so deeper layers keep their temperatures less variable.

The association between the temperatures measured in the sub-base and the solar radiation has certain correlation ($p<0.01$) and it is not significant for the bedding layer temperatures. This could be due to the presence or absence of vehicles occupying the parking bays during the solar radiation hours. Nevertheless, if 2 or 3 hours gap between the maximum daily high air temperatures is considered, the correlation becomes significant ($p < 0.01$) for the temperature measurements at 15cm. The higher correlation indexes increment is observed when 3 hours gap is taken accounted while the correlations indexes for the sub-base temperatures remain approximately unvarying.

This indicates that the heat transfer produced inside the pervious pavement occurs at a lower rate than the cooling processes produced on the surface after the maximum temperature has been reached due to solar radiation.

In order to show if the thermal response varies from rain days to dry ones, a correlation statistical analysis has been done for those data which comprise rain events, while those values registered as rain=0mm are considered dry events; because the summer months of 2008 were atypically wet. The results show that temperatures inside the pavement are highly correlated with the air temperature, inversely correlated with rain and wind, and positively correlated with solar radiation during the rain events. During the dry events the bedding layer temperature are higher correlated with air temperature than the sub-base temperature; there is a positive correlation with wind for the bedding layer and sub-base temperatures, and radiation is correlated with sub-base temperatures (Table 5 and Table 6).

4. Discussion

From the analysis of the results of the reinforced grass pervious pavements under study, 2 main topics can be discussed:

1. Heat transfer mechanism occurred from the surface when solar radiation, convection, and evaporation take place. Heat conduction is more significant inside the pavement and differences in the water content of the porous layers modify the thermal properties inside the permeable pavement. Sub-base and bedding layer temperatures are more influenced by air temperature during the rain events than the dry ones as thermal conductivity increases. The differences between both analyses could be explained when solar radiation diminishes during the day and more rain events take place, the pavement

voids are probably occupied by water, increasing the thermal conductivity of pavement and aggregate bedding layer and registered temperatures are more similar to ambient temperatures. Rain and wind speed are the principal factors inducing surface cooling, therefore the cooling effects are more pronounced during the rain events and lower temperatures in the surface are transmitted to deeper layers within the permeable pavements.

2. Sub-base temperatures are higher than air temperature during the period of study and fluctuate significantly through the day but not as ambient air temperatures do, because it is buffered to daily changes even when there is still influence by the climatic conditions. So it is noticed that the diurnal variation of subsurface temperature is decreasing as the depth of the permeable pavement increases. This can be associated with the insulating ability acquired by these types of permeable pavement and their contribution to the thermal urban environment. The insulating capacity of the pervious pavements is more pronounced during the hottest season, when more solar radiation impacts on the surface and this may cause water evaporation which allows pavement and aggregate voids to be occupied by air.

5. Conclusions

The results obtained provide an indication of the heat transfer processes occurring within the reinforced grass permeable pavements and highlight the insulating capacity of permeable pavements and the thermal behaviour of these structures to analyse the feasibility of employing GSHP systems in the sub-base. The bedding layer and sub-base temperatures of these pavements are higher than air temperature in the conditions of the investigation (permeable pavement structures of 50cm depth and measurements registration during the hottest season and the beginning of the autumn). The heat transfer capacity and the porous pavement enable the sub-base to be used to keep the water temperature significantly different from the air temperature.

However, the results reveal sub-base temperatures higher than air temperatures most of the days. The use of GSHP in cooling mode design, considered for the period of study, would provoke a gradually increment of the water sub-base temperature. The performance of the heat pump would decrease because the increment achieved in the water sub-base would be too fast, and consequently the installation could become not effective. This consequence could be palliated with the cooling effect produced by the rain events, if some precipitation is registered in this season. On the other hand, water levels would have to be taken into account in order to prevent the sub-base to get emptied due to an extraordinary dry season.

Different thermal response could be obtained if the sub-base depth is increased so it could be less influenced by ambient temperature and GSHP technology would become more effective in the cooling mode; and major sub-base area (not restricted to a parking bay dimensions) would avoid the thermal saturation of the heat exchange medium. Current investigation related to this paper involves a complete year monitoring of four types of permeable pavements under convectional construction methods and a detailed study of the influence of climatic variables in the temperature responses. The information obtained will provide an extensive overview of their thermal behaviour in order to evaluate the possibility of using them as a GSHP system all around the year under local weather conditions in north of Spain, in addition to their use as an instrument for rainwater management and urban heat island reduction.

REFERENCES

Asaeda, T. and Ca, V.T. (2000). Characteristics of permeable pavement during hot summer weather and impact on thermal environment. Building and Environment 35, 363-375.

Bäckström, M. (2000). Ground temperature in porous pavement during freezing and thawing. Journal of Transportation Engineering 126 (5), 375-381.

Coupe, S.J., Charlesworth, S., Faraj, A.S. (2009). Combining permeable paving with renewable energy devices: installation, performance and future prospects. 9th International Conference on Concrete Block Paving. Buenos Aires, Argentina, 2009.

del Coz Díaz, J.J., García Nieto, P.J, Domínguez Hernández, J, Suarez Sanchez, A.(2009). Thermal design optimization of lightweight concrete blocks for internal one-way spanning slabs floors by FEM. Energy and Buildings 41 (12), 1276-1287.

Gomez-Ullate, E.; Bayon, J.R.; Coupe, S. and Castro-Fresno, D. (2010). Performance of pervious pavement parking bays storing rainwater in the north of Spain. Water Science & Technology 62(3), 615–621.

Gui, J., Phelan, P.E., Kaloush, K.E., Golden, J.S. (2007). Impact of pavement thermophysical properties on surface temperatures. Journal of Materials in Civil Engineering 19(8), 683-690.

Hermansson, A. (2004). Mathematical model for paved surface summer and winter temperature: comparison of calculates and measured temperatures. Cold Regions Science and Technology 40, 1-17.

Hermansson, A., Charlier, R., Collin, F., Erlingsson, S., Laloui, L., Sršen, M. (2009). Heat transfer in soils. Water in road structures. Dawson, A.R. (ed.). Nottingham Transportation Engineering Centre, University of Nottingham, U.K, pp. 69-79.

Kevern, J.T., Schaefer, V.R. and Wang, K. (2009). Temperature behaviour of pervious concrete system. Transportation Research Record, 2098, 94-101.

Norero, J. and Sauma, E. (2012). Ex-Ante Assessment of the Implementation of an Energy Efficiency Certificate Scheme in Chile. Journal of Energy Engineering, 138(2), 63–72.

Phetteplace, G. (2007). Geothermal heat pumps. Journal of Energy Engineering 133(1), 32-38.

Pratt, C.J. (1999). Use of permeable, reservoir pavement constructions for stormwater treatment and storage for re-use. Water Science and Technology 39(5), 145-151.

Sanner, B., Karytsas, C., Mendrinos, D., Rybach, L. (2003). Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics 32(4), 579-588.

Scholz, M. and Grabowiecki, P. (2007). Review of permeable pavement systems. Building and Environment 42, 3830-3836.

Tota-Maharaj, K.; Grabowiecki, P. and Scholz M. (2009). Energy and temperature performance analysis of geothermal (ground source) heat pumps integrated with permeable pavement systems for urban run-off reuse. International Journal of Sustainable Engineering 2(3), 201-213.

Van Buren, M.A., Watt, W.E., Marsalek, J., Anderson, B.C. (2000). Thermal enhancement of stormwater runoff by paved surfaces. Water Research 34(4), 1359-1371.

Wang, L. and Tseng, C. (2012). Special issue on challenges and opportunities in the 21st century energy infrastructure. Journal of Energy Engineering, 138(2), 31-32.

Wanphen, S. and Nagano, K. (2009). Experimental study of the performance of porous materials to moderate the roof surface temperature by its evaporative cooling effect.

Building and Environment 44, 338-351.

Zhang, H.-F., Ge, X.-S., Ye, H., Jiao, D.-S. (2007). Heat conduction and heat storage characteristics of soils. Applied Thermal Engineering 27, 369-373.

Figure

Figure 1. Location of the permeable pavement bays selected in the experimental parking lot

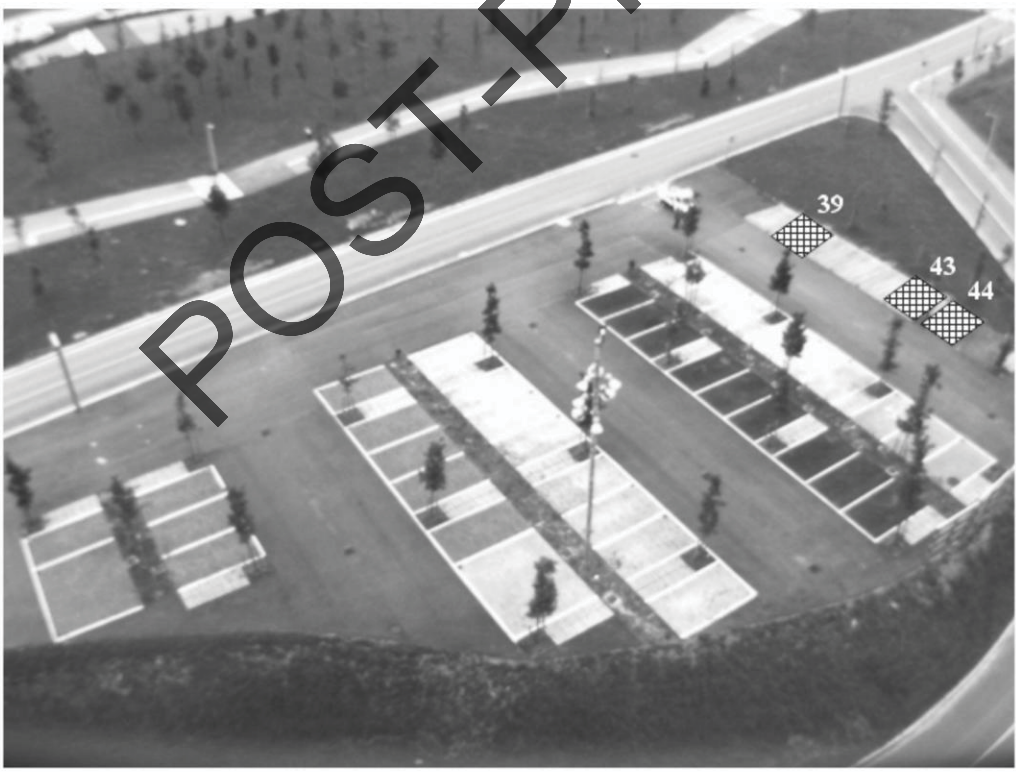

Figure 1. Location of the permeable pavement bays selected in the experimental parking lot

Figure

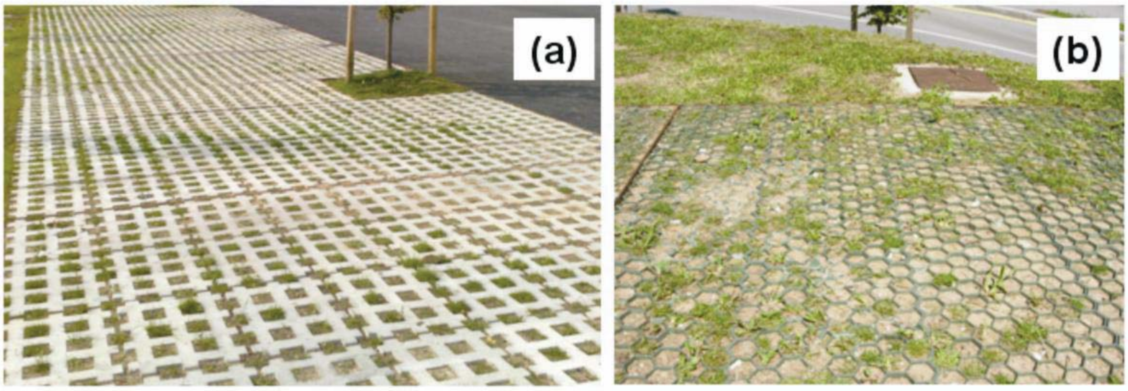

Figure 2. Permeable pavement types under study: (a) Reinforced grass with concrete grid and (b) reinforced grass with plastic grid

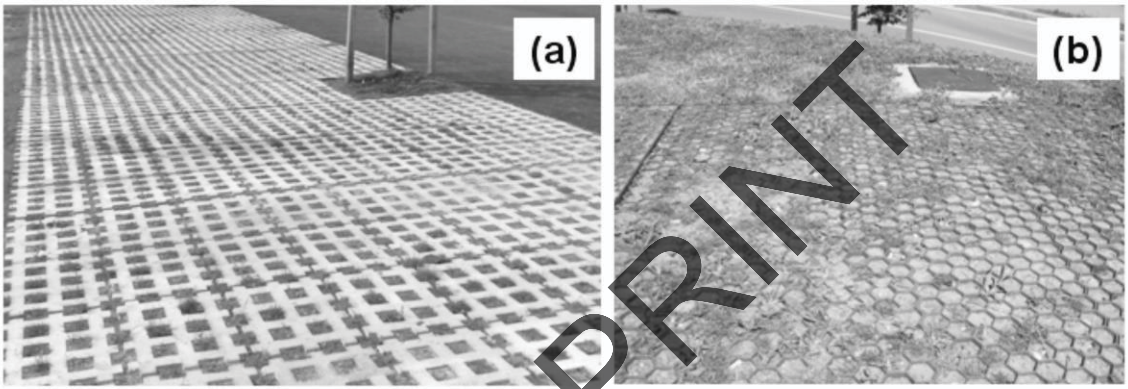

Figure 2. Permeable pavement types under study: (a) Reinforced grass with concrete grid and (b) reinforced grass with plastic grid

Figure

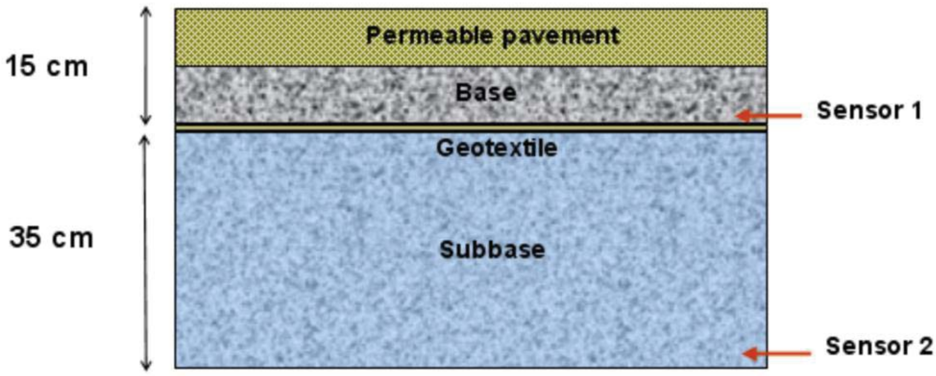

Figure 3. Cross section of permeable pavement parking bay

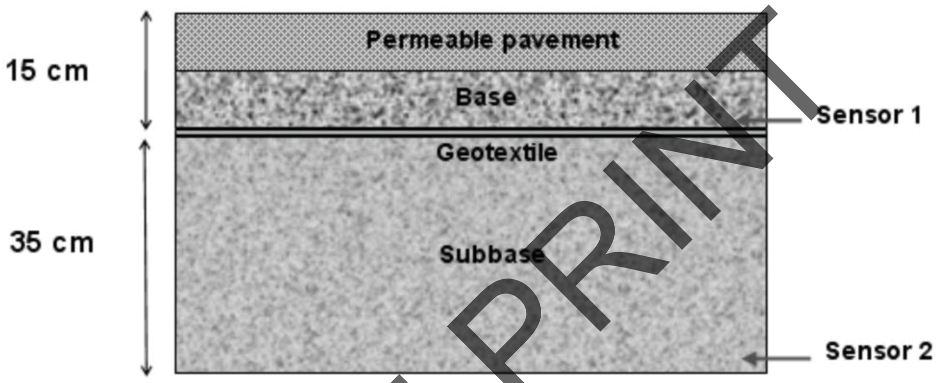

Figure 3. Cross section of permeable pavement parking bay

Figure

Figure 4. Register box with datalogger and temperature probes

Figure 4. Register box with datalogger and temperature probes

Figure

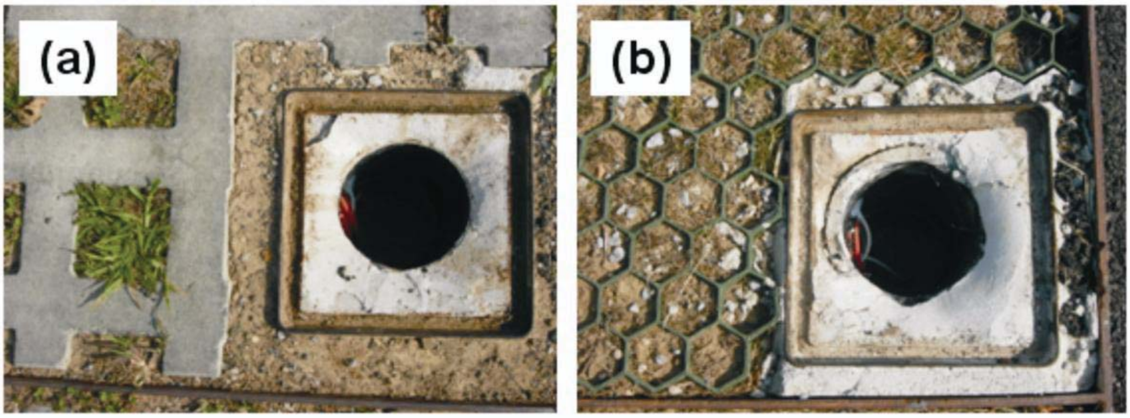

Figure 5. Connection tubes to install the temperature probes to 15cm and 50cm depth in the (a) reinforced grass with concrete grid and (b) reinforced grass with plastic grid parking bays

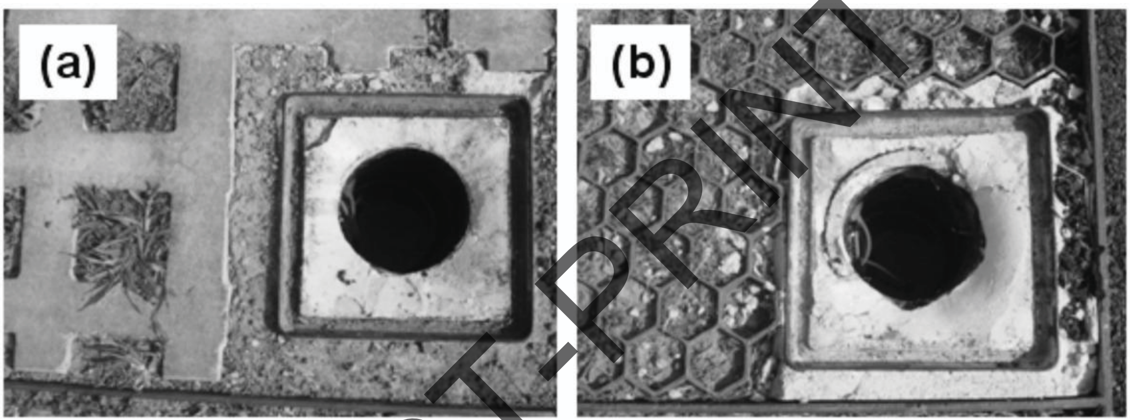

Figure 5. Connection tubes to install the temperature probes to 15cm and 50cm depth in the (a) reinforced grass with concrete grid and (b) reinforced grass with plastic grid parking bays

Figure

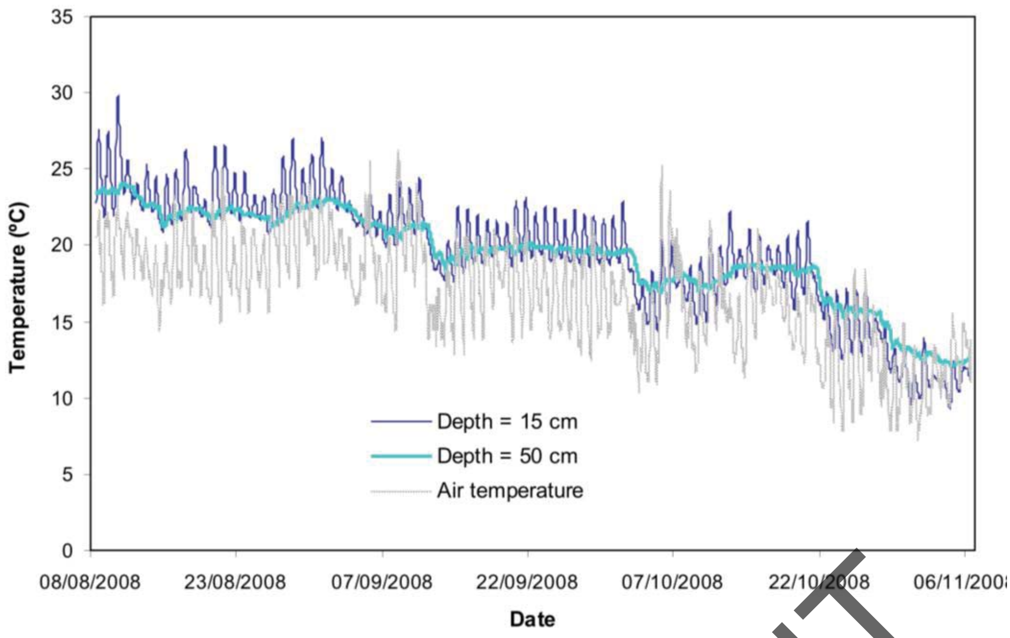

Figure 6. Temperature response of the parking bay 39 (Reinforced grass with concrete grid)

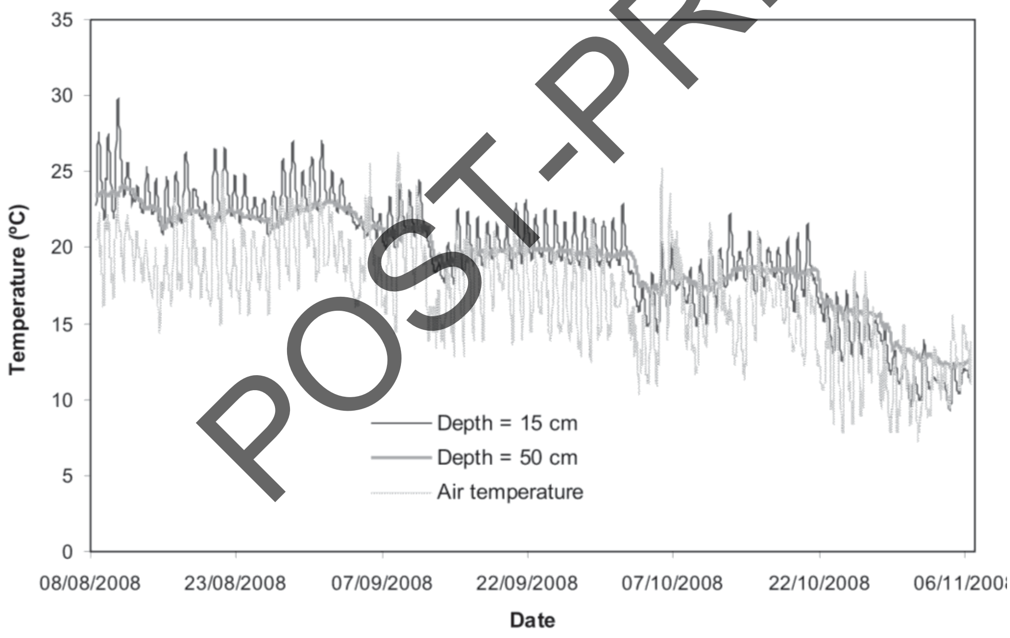

Figure 6. Temperature response of the parking bay 39 (Reinforced grass with concrete grid)

Figure

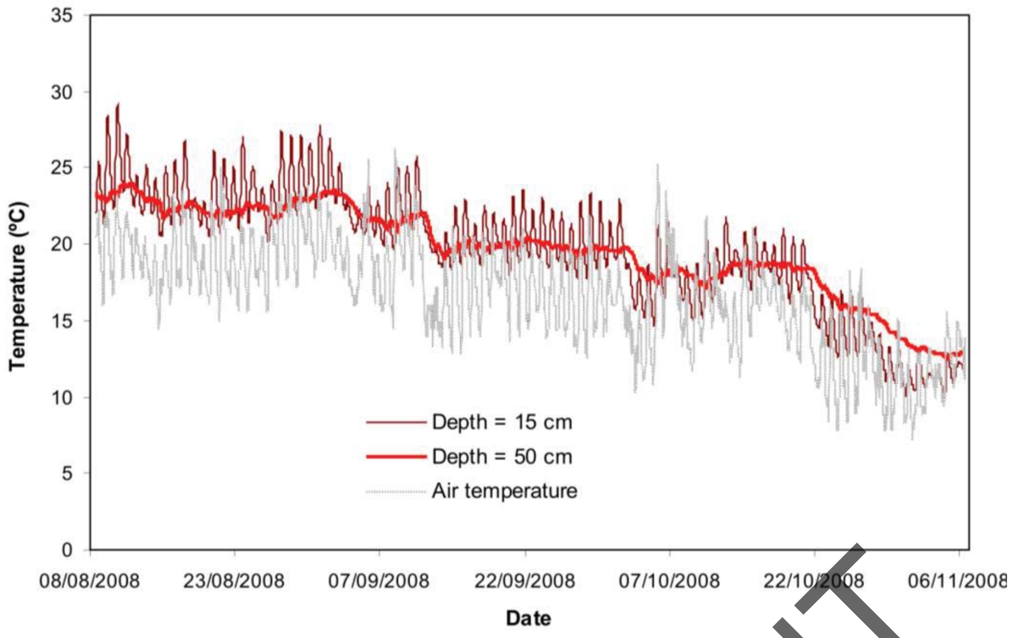

Figure 7. Temperature response of the parking bay 43 (Reinforced grass with concrete grid)

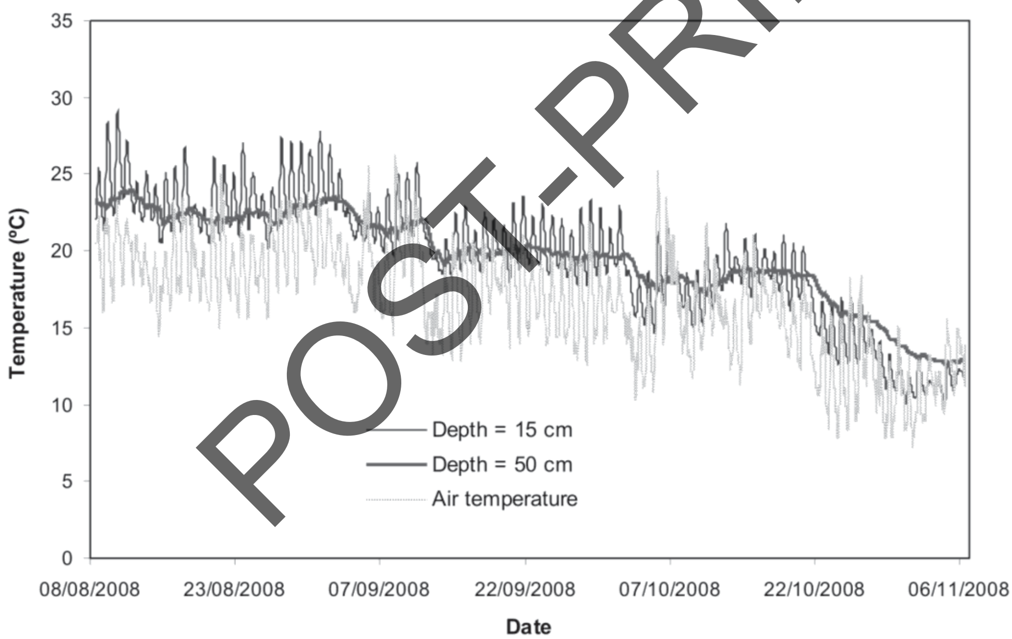

Figure 7. Temperature response of the parking bay 43 (Reinforced grass with concrete grid)

Figure

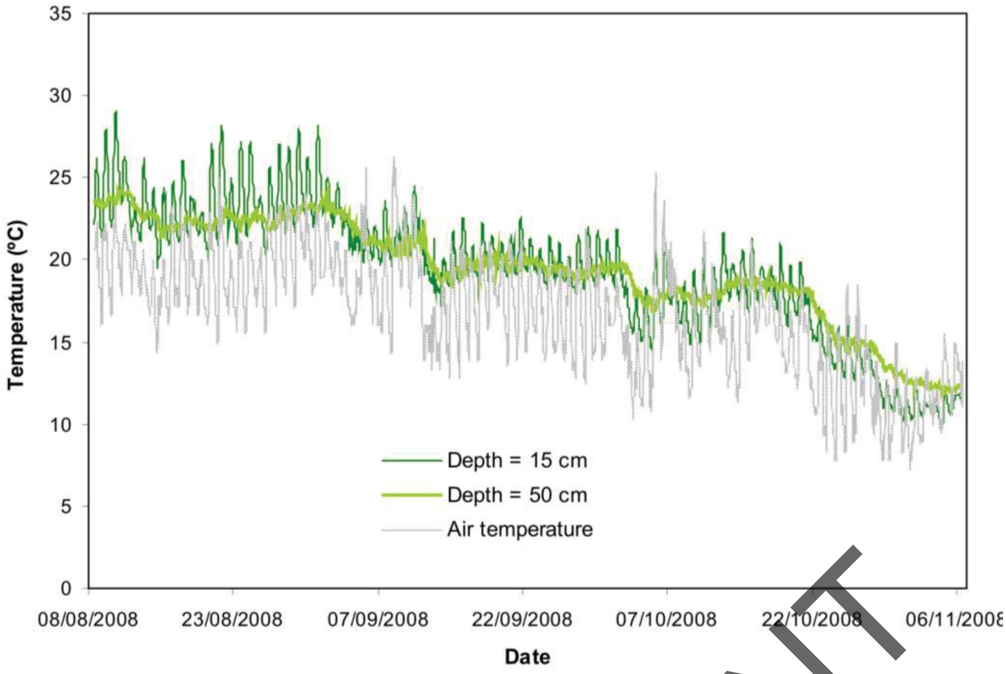

Figure 8. Temperature response of the parking bay 44 (Reinforced grass with plastic grid)

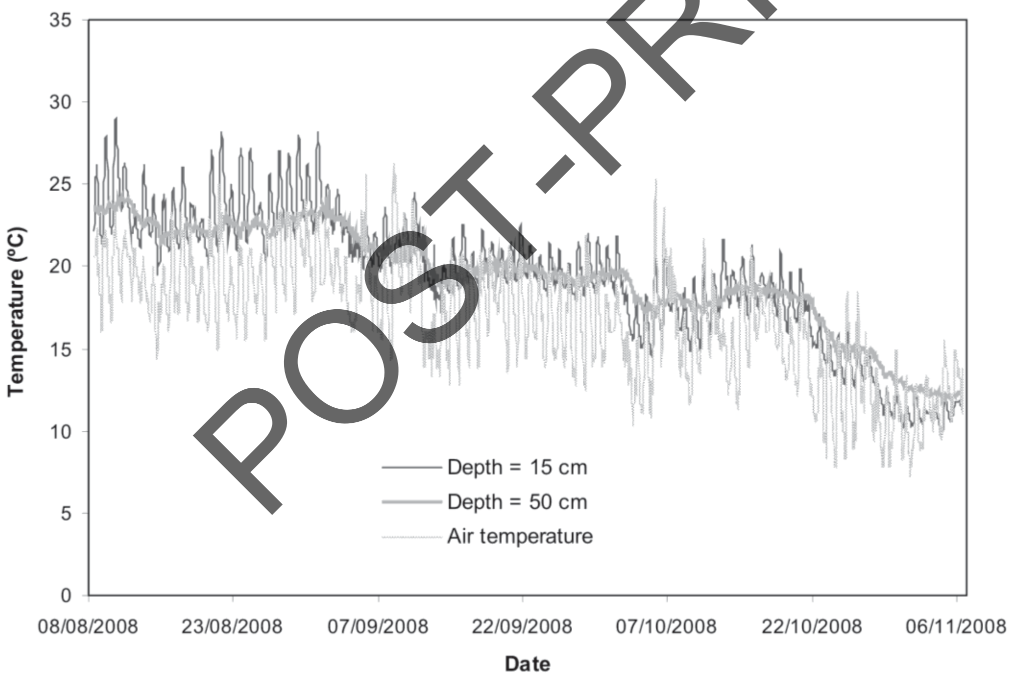

Figure 8. Temperature response of the parking bay 44 (Reinforced grass with plastic grid)

Figure

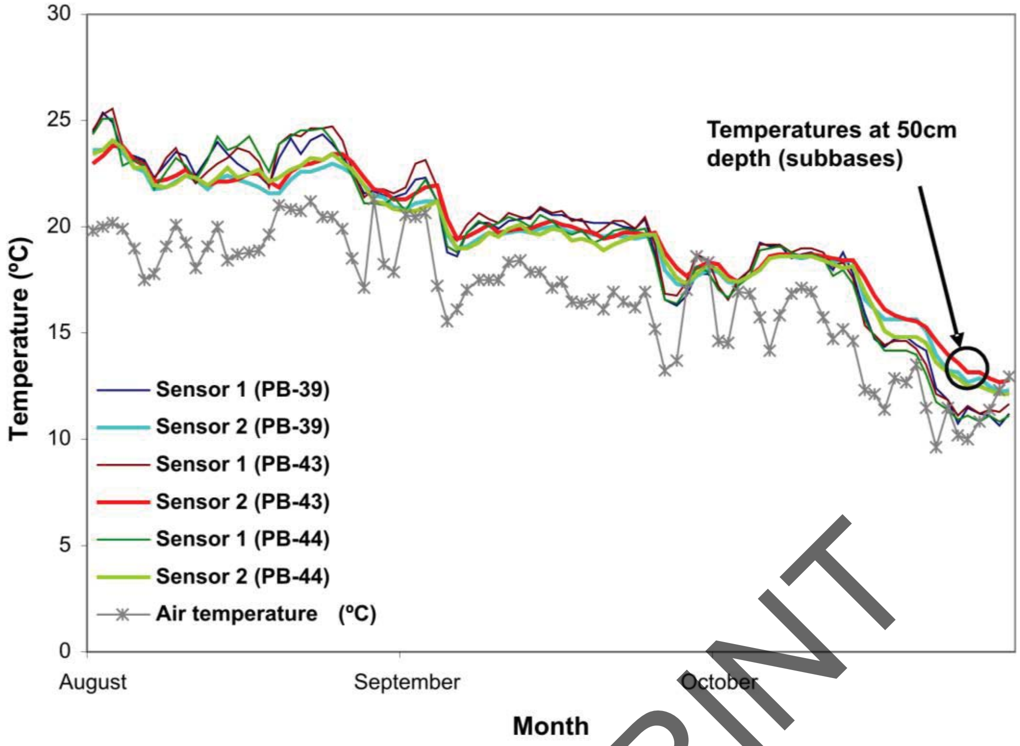

Figure 9. Daily mean temperatures measured during the period of study

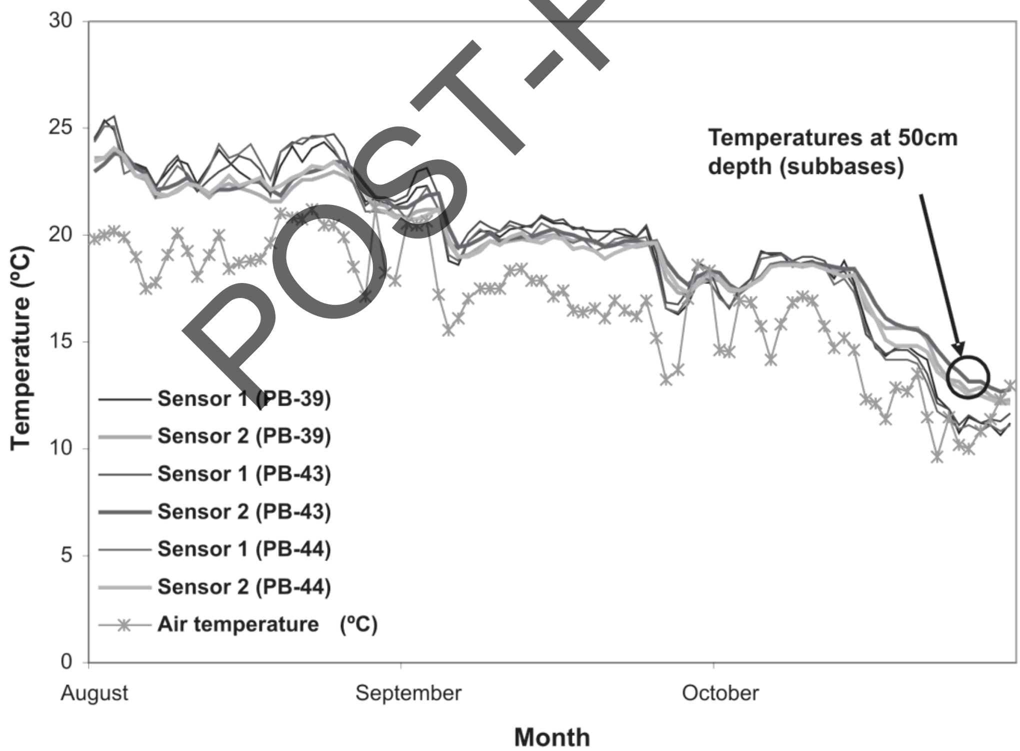

Figure 9. Daily mean temperatures measured during the period of study

PARKING BAY	SURFACE	BASE	GEOTEXTILE	SUBBASE
PB-10	Concrete block	Limestone gravel (2-6 mm)		Limestone aggregate (4-20 mm and 10-63 mm)
PB-11	Concrete block	Limestone gravel (4-8 mm)		Limestone aggregate (4-20 mm)
PB-18	Concrete block	Limestone gravel (4-8 mm)	Danofelt® DY 150	Limestone aggregate (4-20 mm)
PB-19	Concrete block	Limestone gravel (4-8 mm)	Danofelt® DY 150	Limestone aggregate (4-20 mm)
PB-27	Porous asphalt PA12	Limestone gravel (4-20 mm)	Danofelt® DY 150	Limestone aggregate (4-20 mm)
PB-28	Porous asphalt PA12	Limestone gravel (4-20 mm)		Limestone aggregate (4-20 mm)
PB-36	Porous concrete	Limestone gravel (4-20 mm)		Limestone aggregate (4-20 mm)
PB-37	Porous concrete	Limestone gravel (4-20 mm)		Limestone aggregate (4-20 mm)
PB-39	Reinforced grass with concrete grid	Limestone gravel (4-8 mm)	Polifelt® TS30	Limestone aggregate (4-20 mm)
PB-43	Reinforced grass with concrete grid	Limestone gravel (4-8 mm)	Danofelt® DY 150	Limestone aggregate (4-20 mm)
PB-44	Reinforced grass with plastic grid	Limestone gravel (4-8 mm)	Danofelt® DY 150	Limestone aggregate (4-20 mm)

Table 1. Permeable pavements bays characteristics and construction materials employed

Test Statistics[b,c]			
Parking bay	PB-39	PB-43	PB-44
Z	-15.161[a]	-11.597[a]	-8.518[a]
p value	0.000	0.000	0.000

a. Based on positive ranks
b. First period
c. Wilcoxon Signed Ranks Test

Table 2. Wilcoxon signed-ranks test between the temperatures obtained at 15cm and 50cm for each parking bay during the first period of study

Test Statistics[b,c]			
Parking bay	PB-39	PB-43	PB-44
Z	-20.570[a]	-23.011[a]	-22.265[a]
p value	0.000	0.000	0.000

a. Based on negative ranks
b. Second period
c. Wilcoxon Signed Ranks Test

Table 3. Wilcoxon signed-ranks test between the temperatures obtained at 15cm and 50cm for each parking bay during the second period of study

Table
Click here to download Table: Table4.doc

Temperature sensors	Spearman's Rho	Air temperature (ºC)	Relative humidity (%)	Rain (mm)	Wind speed (m/h)	Radiation (10 KJ/m²)
Sensor 1 (PB-39; 15cm)	Correlation coefficient	0.682**	-0.086**	-0.038*	0.133**	-0.045
	Sig. (bilateral)	0.000	0.000	0.031	0.000	0.062
	N	3524	3143	3143	3143	1762
Sensor 2 (PB-39; 50cm)	Correlation coefficient	0.513**	0.065**	0.025	0.025	0.098**
	Sig. (bilateral)	0.000	0.000	0.163	0.169	0.000
	N	3524	3143	3143	3143	1762
Sensor 1 (PB-43; 15cm)	Correlation coefficient	0.670**	-0.047**	-0.026	0.126**	-0.118**
	Sig. (bilateral)	0.000	0.008	0.148	0.000	0.000
	N	3524	3143	3143	3143	1762
Sensor 2 (PB-43; 50cm)	Correlation coefficient	0.515**	0.071**	0.047**	0.044*	0.115**
	Sig. (bilateral)	0.000	0.000	0.008	0.013	0.000
	N	3524	3143	3143	3143	1762
Sensor 1 (PB-44; 15cm)	Correlation coefficient	0.711**	-0.071**	-0.035	0.139**	0.008
	Sig. (bilateral)	0.000	0.000	0.052	0.000	0.726
	N	3524	3143	3143	3143	1762
Sensor 2 (PB-44; 50cm)	Correlation coefficient	0.517**	0.085**	0.042*	0.038*	0.079**
	Sig. (bilateral)	0.000	0.000	0.018	0.031	0.001
	N	3524	3143	3143	3143	1762

**. The correlation is significant at level 0.01 (bilateral).
*. The correlation is significant at level 0.05 (bilateral).

Table 4. Correlation between climatic variables and the temperatures measured during the first period

Temperature sensors	Spearman's Rho	Air temperature (ºC)	Relative humidity (%)	Rain (mm)	Wind speed (m/h)	Radiation (10 KJ/m²)
Sensor 1 (PB-39; 15cm)	Correlation coefficient	0.473**	0.075*	-0.158**	-0.228**	-0.007
	Sig. (bilateral)	0.000	0.042	0.000	0.000	0.893
	N	794	739	739	739	397
Sensor 2 (PB-39; 50cm)	Correlation coefficient	0.089*	0.190**	-0.288**	-0.382**	0.047
	Sig. (bilateral)	0.012	0.000	0.000	0.000	0.354
	N	794	739	739	739	397
Sensor 1 (PB-43; 15cm)	Correlation coefficient	0.479**	0.073*	-0.224**	-0.249**	-0.056
	Sig. (bilateral)	0.000	0.049	0.000	0.000	0.263
	N	794	739	739	739	397
Sensor 2 (PB-43; 50cm)	Correlation coefficient	0.105**	0.137**	-0.290**	-0.372**	0.113*
	Sig. (bilateral)	0.003	0.000	0.000	0.000	0.025
	N	794	739	739	739	397
Sensor 1 (PB-44; 15cm)	Correlation coefficient	0.470**	0.077*	-0.226**	-0.244**	0.044
	Sig. (bilateral)	0.000	0.037	0.000	0.000	0.387
	N	794	739	739	739	397
Sensor 2 (PB-44; 50cm)	Correlation coefficient	0.088*	0.174**	-0.281**	-0.382**	0.037
	Sig. (bilateral)	0.013	0.000	0.000	0.000	0.457
	N	794	739	739	739	397

**. The correlation is significant at level 0.01 (bilateral).
*. The correlation is significant at level 0.05 (bilateral).

Table 5. Correlation between climatic variables and the temperatures measured during the second period

Parking bay types	Concrete block	Porous asphalt	Reinforced grass with concrete grid
PARAMETERS	Mean* (N=3)	Mean* (N=3)	Mean* (N=3)
Turbidity (NTU)	8.133 (1.966-14.300)	42.000 (-70.525-154.525)	16.167 (-10.929-43.262)
Conductivity (µS)	427.333 (273.149-581.516)	310 (281.351-338.648)	427.333 (367.696-486.969)
Temperature (ºC)	22.067 (21.549-22.583)	22.233 (21.292-23.173)	21.033 (20.889-21.176)
Dissolved oxygen (mg/l)	4.223 (1.663-6.783)	3.667 (3.302-4.030)	2.523 (0.963-4.082)
Ph	7.713 (7.163-8.263)	7.873 (7.797-7.949)	7.62 (7.168-8.071)
Total hardness (mg/l)	136.467 (85.408-187.524)	136.467 (110.937-161.995)	166.133 (140.604-191.662)
OQD (mg/l)	5.323 (1.054-9.591)	10.527 (8.845-12.208)	6.56 (3.311-9.808)
Total phosphorus (mg/l)	0.019 (-0.013-0.051)	0.023 (0.004-0.041)	0.026 (0.019-0.031)
Total nitrogen (mg/l)	0.738 (-0.332-1.808)	0.5 (0.097-0.901)	0.38 (0.165-0.594)
Heterotrophic bacteria 22 ºC (CFU/ml)	5.567E+07 (1.41E+07-9.73E+07)	1.968E+09 (-2.51E+09-6.44E+09)	1.415E+09 (-1.53E+09-4.36E+09)
Heterotrophic bacteria 36 ºC (CFU/ml)	4.153E+08 (-1.17E+09-2.00E+09)	2.317E+07 (-8.85E+06-5.52E+07)	3.150E+07 (-1.30E+07-7.60E+07)

*95 % confidence interval

Table 6. Means for water analysis parameters of the permeable pavement parking bays selected