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WATER QUALITY AND QUANTITY ASSESSMENT OF PERVIOUS PAVEMENTS PERFORMANCE IN EXPERIMENTAL CAR PARK AREAS

Luis A. Sañudo-Fontaneda[1]*, Susanne M. Charlesworth[2], Daniel Castro-Fresno[1], Valerio C.A. Andres-Valeri[1], Jorge Rodriguez-Hernandez[1]

[1] Construction Technology Research Group (GITECO). Dept. of Transport, Project and Process Technology, ETSICCP, Universidad de Cantabria, 39005 Santander, Spain.

[2] Sustainable Drainage Applied Research Group (SUDS ARG). Department of Geography, Environment and Disaster Management. Coventry University. Faculty of Business, Environment and Society, CV1 5LW, UK.

*Corresponding author email: sanudola@unican.es

ABSTRACT
Pervious pavements have become one of the most used Sustainable Urban Drainage Systems techniques in car parks. This research paper presents the results of monitoring water quality from several experimental car park areas designed and constructed in Spain with bays made of interlocking concrete blocks pavement, porous asphalt, polymer modified porous concrete and reinforced grass with plastic and concrete cells. Moreover, two different sub-base materials were used (limestone aggregates and Basic Oxygen Furnace slag). This study therefore encompasses the majority of the materials used as permeable surfaces and sub-base layers all over the world. Effluent from the test bays were monitored for Dissolved Oxygen, pH, Electric Conductivity, Total Suspended Solids, Turbidity and Total Petroleum Hydrocarbons in order to analyze the behaviour showed by each combination of surface and sub-base materials. In addition, permeability tests were undertaken in all car parks using the "Laboratorio Caminos Santander" permeameter and the Cantabrian Portable Infiltrometer. All results are presented together with the influence of surface and sub-base materials on water quality indicators using bivariate correlation statistical analysis at a confidence level of 95%. The polymer modified porous concrete surface course in combination with limestone aggregate sub-base presented the best performance.

KEYWORDS: infiltration; permeable surfaces; stormwater; SUDS.

1. INTRODUCTION

There is broad agreement of the necessity to increase permeable surfaces in urban areas to reduce runoff peak flows (Dietz, 2007). In this context Sustainable Urban Drainage Systems (SUDS) as Pervious Pavements Systems (PPS) have important advantages (Sañudo-Fontaneda et al., 2013), not only in the reduction of runoff by decreasing impermeable areas (Rushton, 2001), but also in the reduction of pollutants (Coupe et al, 2003), recharge of aquifers (Ferguson, 2011), erosion control (Wright, 2008) and increased urban amenity (Ellis et al., 2004). The main applications of PPS in urban areas are car parks for light traffic where PPS have the potential to occupy large urban areas (Shu et al., 2011), access roads for residential streets, parking areas and roads for recreational facilities such as golf courses and bike lanes, amongst others (Scholz and Grabowiecki, 2009).

There are many field studies of the efficiency of PPS such as Collins et al. (2008) in the USA, Pratt et al. (1995) in the UK, Lucke and Beecham (2011) in Australia, Pagotto et al. (2000) in France, and Acioli et al. (2005) in Brazil, amongst others. In spite of the fact that the results are slightly different depending on the climatic conditions of the region where the car park is located, important benefits in terms of runoff reduction, water quality and amenity were demonstrated in all of them.

The main aim of this paper was to compare the water quality and water quantity of experimental in-use PPS constructed with four different surfaces: interlocking concrete block pavement (ICBP), porous asphalt (PA), polymer modified porous concrete (PMPC) and grass reinforced with plastic (GRPC) or concrete cells (GRCC), and two different sub-bases: limestone aggregates (LA) and Basic Oxygen Furnace slag (BOF-slag). The three experimental parking areas, called "La Guía" and "Parque Tecnológico", located in Gijón and "Las Llamas", in Santander, were all in the north of Spain. The impacts on water quality parameters of BOF-slag used as a sub-base layer were compared with limestone aggregate materials, whilst the influence of the surface course was analyzed through the use of bivariate correlations and a descriptive analysis of all water quality parameters shown in box plots.

2. RESEARCH METHODOLOGY

2.1. Experimental car park features

All parking areas were located on the north coast of Spain which has an annual average temperature and precipitation of 15ºC and 1,000 mm, respectively, with similar rainfall patterns at both locations. The occupational level of all the car park bays in all the parking areas during the research period was the same (nearly 100%) which made them comparable for water quality and quantity analysis. Table 1 details the materials, layers, number of bays, and dimensions in each of the experimental car park areas. Figure 1 shows the general car park bay features and details of the manhole access for sampling.

Table 1. Parking bay sections monitored at each car park area with their thickness.

Location	**Layer**	**PERMEABLE SURFACE TYPE**					
		ICBP (Aquaflow)	**ICBP (Monserrat)**	**PA-12 (Bustos and Pérez 2007)**	**PMPC (Pindado et al. 1999)**	**GRCC**	**GRPC**
"La Guía" (Gijón) 798 bays **(15 monitored)** *2005* Bay dimensions 5.0 m × 2.5 m	**Surface**	—	100 mm	100 mm (2 layers of 50 mm)	—	—	80 mm
	Base	—	Clean limestone aggregate (50-70 mm)		—	—	Clean limestone aggregate (50-70 mm)
	Geotextile	—	Terratest TMA 125	Geotextile (Amopave)	—	—	—
	Sub-base (350 mm)	—	Recycled aggregates (3 bays)	Recycled aggregates (3 bays)	—	—	Blast furnace slag with a low infiltration rate
			Clean LA without fines (3 bays)	Clean LA without fines (3 bays)			
"Las Llamas" (Santander) 45 bays **(45 monitored)** *2008* Bay dimensions 4.2 m × 2.4 m	**Surface**	80 mm	100 mm	80 mm	80 mm	90 mm	80 mm
	Base	Clean limestone aggregates (50-70mm)					
	Geotextile	Inbitex (4bays)	Polyfelt TS30 (4bays)	Polyfelt TS30 (4bays)	Polyfelt TS30 (4bays)	Polyfelt TS30 (2bays)	Polyfelt TS30 (2bays)
		One-Way (4bays)	Danofelt PY150 (4bays)	Danofelt PY150 (4bays)	Danofelt PY150 (4bays)	Danofelt PY150 (2bays)	
		Without geotextile (2bays)	Without geotextile (1bay)	Without geotextile (1bay)	Without geotextile (1bay)	Without geotextile (2bays)	
	Sub-base	Clean LA without fines (350-370mm)					
"Parque Tecnológico" (Gijón) 51 bays **(8 monitored)** *2010* Bay dimensions 4.2 m × 2.4 m	**Surface**	—	100 mm (4bays)	80 mm (4bays)	—	—	—
	Base and geotextile	—	50 mm of clean limestone aggregates (4-8 mm)	70 mm of clean limestone aggregates (4-8 mm)	—	—	—
	Sub-base	350 mm of BOF-slag					

Each car park bay in the three experimental parking areas was designed and constructed in order to store stormwater separately (Gomez-Ullate et al. (2010). This was achieved by tanking the bays individually using a waterproof bituminous membrane, protected from damage due to the sub-base aggregates with a geotextile. The sub-base layer was added followed by the geotextile to separate it from the base layer aggregates, and then the surface course laid on top.

The particle size distributions of the sub-base layer aggregates (LA and BOF-slag) are shown in Table 2. The chemical composition of the BOF-slag was described in Andrés-Valeri et al. (2013).

Table 2. Sub-base of aggregates (LA and BOF-slag) particle size distribution.

Sub-base material	Spanish UNE sieves (mm)										
	40	25	20	12.5	8	4	2	0.5	0.25	0.125	0.063
LA (% passing)		70-100	50-65	30-65	30-40	10-14	-	-	-	-	-
BOF-slag aggregates (% passing)	-	100	75-100	-	45-73	31-54	20-40	9-24	5-18	-	0-9

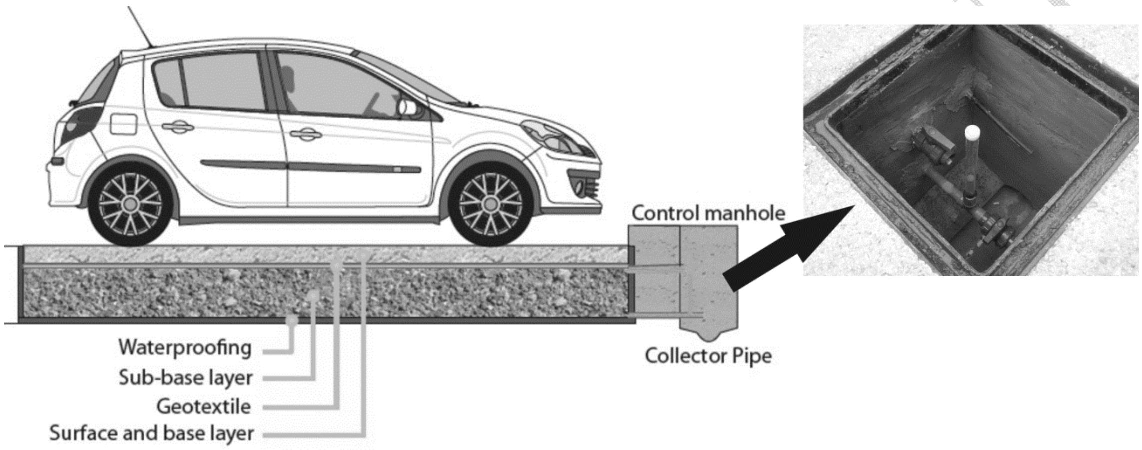

Figure 1. (Left) Generalised scheme of the PPS parking bay for all experimental parking areas and (right) the control manhole.

2.2. Methodology for measuring water quality

Water quality analysis was undertaken based on the following water quality parameters: total suspended solids (TSS) and turbidity, which are relevant indicators for water reuse according to the Spanish Royal Decree RD, 1620/2007. Others including pH, Electric Conductivity (EC) and Dissolved Oxygen (DO) were chosen as they represent water quality parameters used in previous research (Gomez-Ullate et al. 2010). Finally, Total Petroleum Hydrocarbons (TPH) were measured since they have been found to be one of the most common pollutants present in runoff (Horner et al., 1994).

All experimental car park bays in all three parking areas were monitored by collecting three 1 L container of effluent water from each control manhole (see Figure 1) once a month during the research period of least 12 months for all parking areas. The following were measured on-site: pH, EC and DO using the multi-parameter analyzer HACH HQ-40D, whilst the remaining parameters (TSS, turbidity and TPH) were analyzed at the Sustainable Urban Drainage Systems laboratory of the University of Cantabria (SUDSlab) within 24 hours of collection.

A statistical analysis gave average outflow water quality of all the parking areas depending on the type of permeable surface and sub-base materials used. It allowed comparison of the behaviour of different materials and layers since the rainfall patterns associated with all the parking areas and the percentage of occupation of each car park bay by vehicles was similar. Therefore, neither specific rainfall events, nor surface runoff water inflow into each car park bay were taken into account since they were not the main purpose of this study.

2.3. Methodology for measuring water quantity

To assess the water quantity aspects of the whole parking area, both the “Laboratorio Caminos Santander” (LCS) permeameter (CEDEX, 2000) and the Cantabrian Portable (CP) Infiltrometer device were used in the field to measure permeability and infiltration behaviour respectively (Fernández-Barrera et al., 2008).

Three permeability tests with three repetitions each per test were undertaken for all car park bays with porous surfaces (PA-12 and PMPC) using the LCS permeameter, in order to obtain an average value. No LCS tests were carried out for the ICBP and GRPC or GRCC surfaces.

However, it was possible to use the CP Infiltrometer on all permeable surfaces at “La Guía” and “Las Llamas” to obtain their infiltration capacity. This measure is based on the height of inundation as is described in Fernández-Barrera et al. (2008). Three different rainfall intensities of five minutes duration were simulated per measurement corresponding to ten years (78 mm/h), fifty years (115 mm/h) and one hundred years return period (142 mm/h) in the city of Gijón, and ten years (98 mm/h), fifty years (155 mm/h) and one hundred years return period (178 mm/h) in Santander over the ICBP and PA-12 surfaces, respectively.

3. RESULTS AND DISCUSSION

3.1. Water quality

Bivariate correlation was carried out using IBM SPSS Statistics 22 in order to assess the relationship between the different surface courses and sub-surface layers, and resultant water quality parameters. These analyses, at a confidence level of 95%, are shown in Table 3.

Table 3. Spearman Rho coefficients.

		Surface	Sub-base	pH	DO	EC	TSS	Turbidity	TPH
Surface	Correlation coefficient	1.000	-0.426**	-0.398**	-0.102	-0.079	0.375**	0.400**	-0.340**
	Significance (Bilateral)	—	0.000	0.000	0.216	0.337	0.003	0.001	0.002
Sub-base	Correlation coefficient	-0.426**	1.000	0.693**	0.157	0.684**	-0.453**	-0.541**	0.689**
	Significance (Bilateral)	0.000	—	0.000	0.056	0.000	0.000	0.000	0.000

** Correlation is significant at the 0.01 level (bilateral).

It was demonstrated that both surface and sub-base layers were significantly correlated with water quality parameters in almost all cases except for surface materials which were not linearly related with DO and EC (see significance values for all coefficients in Table 3).

Higher correlation coefficients were found for sub-base materials and all water quality parameters than was the case for surface materials (Table 3). This fact is also illustrated in Figures 2 and 3 where the difference between the average values for all water quality parameters were notable depending on the type of sub-base material used.

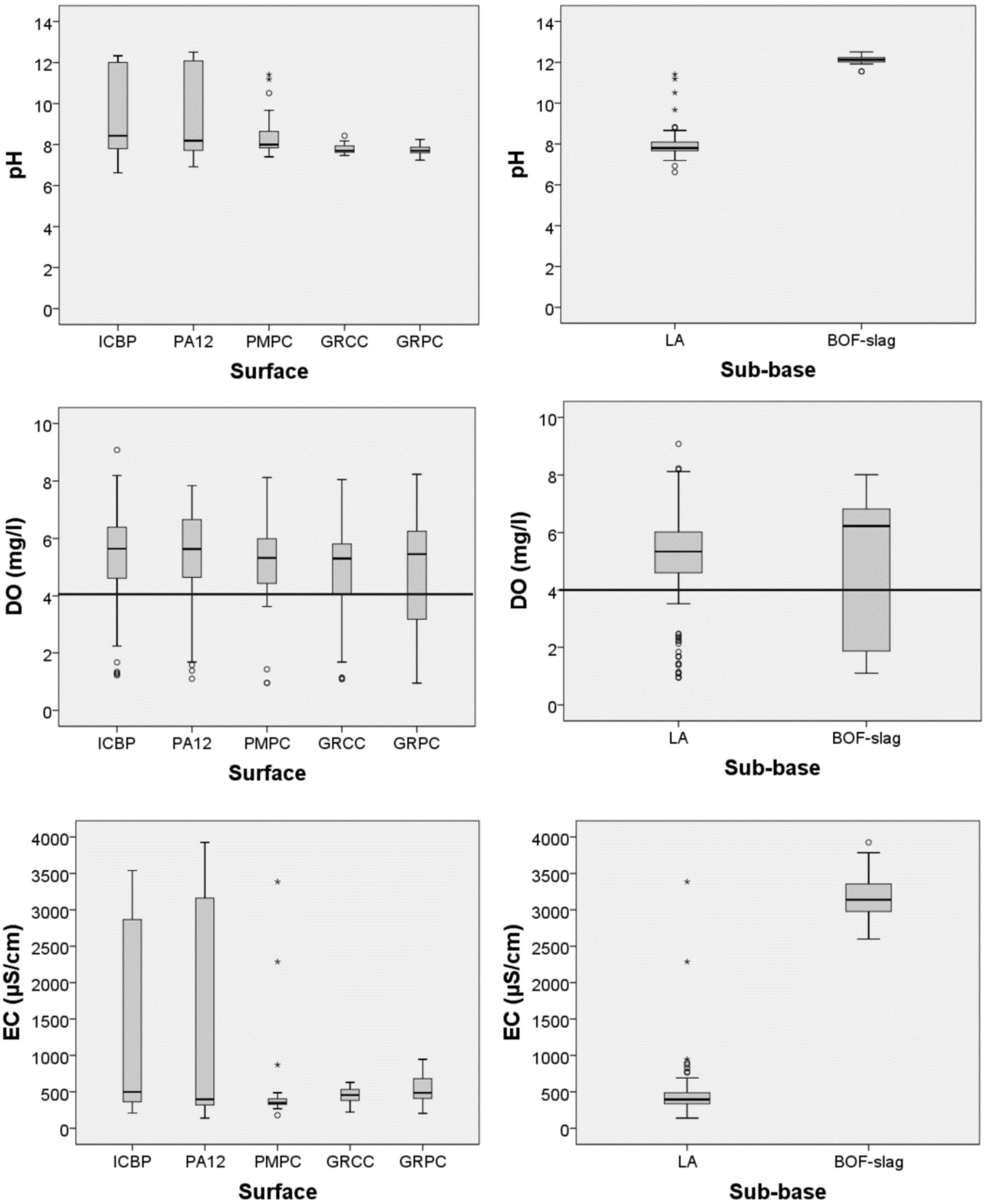

Figure 2. Boxplot of pH, DO and EC values obtained through the use of the multi-parameter analyzer HACH HQ-40D in all parking areas.

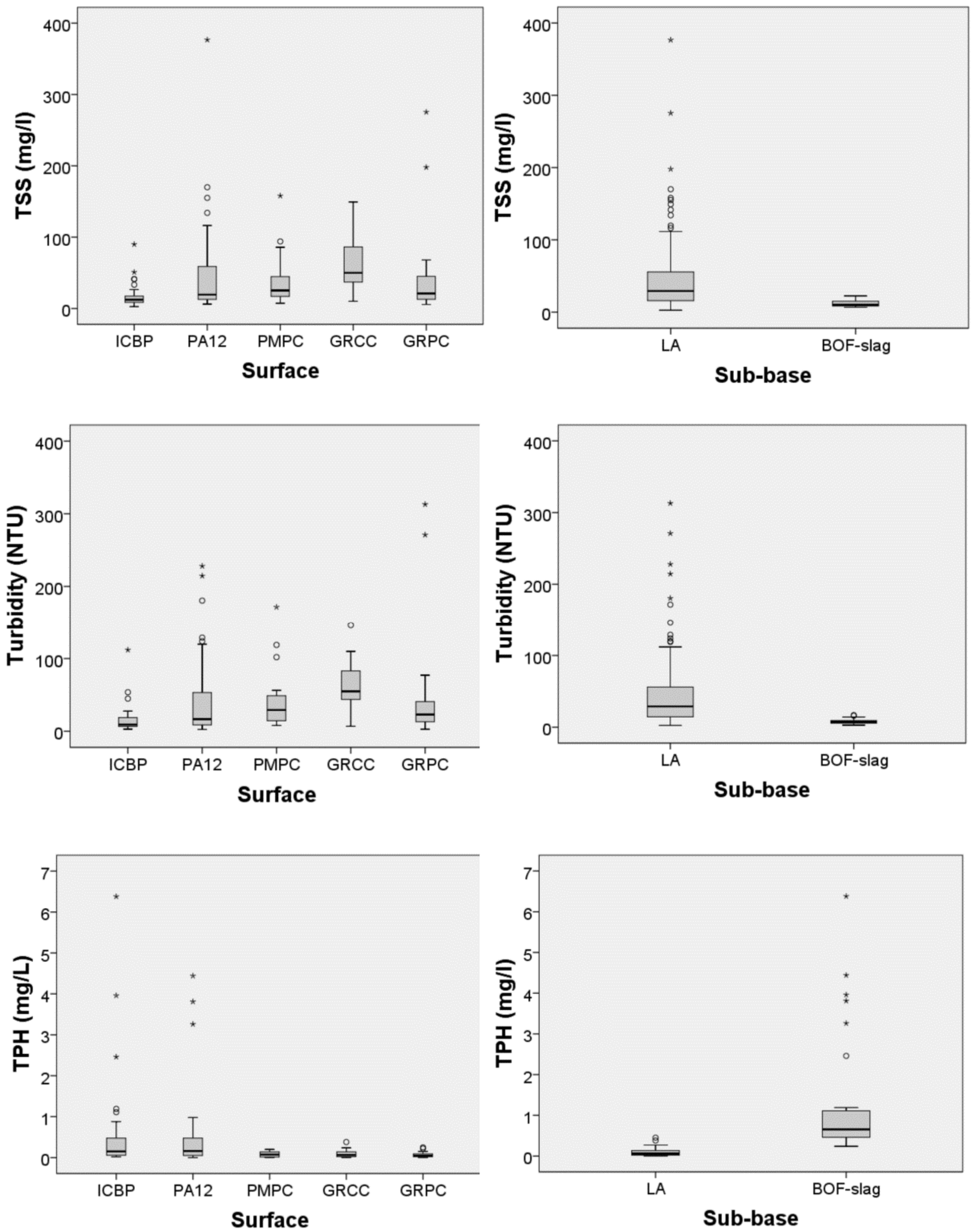

Figure 3. Boxplot of TSS, turbidity and TPH values obtained in laboratory for all water samples taking from all parking areas.

Correlation coefficients obtained in Table 3 for the sub-bases were high or moderate (high for values between 0.60-0.79; moderate for those between 0.40-0.59) for the surfaces, correlation coefficients were moderate or low (moderate for values between 0.40-0.59; low for those between 0.20-0.39) based on the classification given by Bisquerra (1987). Nevertheless, a more in-depth statistical analysis was required to check the significance differences between water quality parameters depending on the surfaces and the sub-base materials used. Therefore, a Kruskal Wallis test was undertaken for surfaces, while the Mann-Whitney test was developed to analyze the sub-base materials as shown in Table 4.

Table 4. Results of the significance tests of Kruskal Wallis for the case of the surfaces and Mann-Whitney for the case of the sub-base materials.

		pH	DO	EC	TSS	Turbidity	TPH
Kruskal Wallis test*	Chi-square	29.401	3.826	12.096	33.995	35.564	19.593
	Asymptotic Significance	0.000	0.430	0.017	0.000	0.000	0.001
Mann-Whitney test**	Mann-Whitney U	0.000	1393.0	23.0	623.0	394.0	13.5
	Asymptotic Significance (Bilateral)	0.000	0.056	0.000	0.000	0.000	0.000

*Grouping variable for the Kruskal Walis tests: surface.
** Grouping variable for the Mann-Whitney test: sub-base.

Both analyses (Table 4) confirmed the results shown in Table 3 of the bivariate correlation between surfaces and water quality parameters and sub-base materials and water quality parameters apart from that of DO (for both surface and sub-base) as is also confirmed in Table 3.

Differences observed between both types of sub-base materials and measured values of pH and EC were significant (Table 3), highlighting the highly alkaline character of the BOF-slag sub-base due to its chemical composition, being rich in calcium oxide and other metal compounds, which also resulted in high EC values as shown on Figure 2. No significant differences were observed, however, in the case of DO values for either surface or sub-base materials. It was found that average values registered in both sub-base materials always exceeded the DO limit of 4 mg/L required for good quality water (Figure 2) according to the Spanish Royal Decree RD, 927/1988.

Despite there being little statistical relationship between DO and EC for the surface materials, nonetheless they were highly linearly correlated with TSS, turbidity and TPH values, with car park bays containing ICBP, PA-12, PMPC and GRPC presenting the lowest average TSS and turbidity values (Figure 3), as well as EC (Figure 2). The influence of the sub-base consisting of BOF-slag aggregates modified the extreme values of EC for ICBP and PA-12 surfaces (Figure 2), where this kind of sub-base material was used. This tendency was also confirmed in Figure 2 when comparing the EC values for the two types of sub-base materials utilized in this research.

More hydrocarbons were retained in association with bays containing PMPC due to the filtering effect of its porous surface, and also GRCC and GRPC due to the retention of more oils as solids in their surface layers than was found for ICBP and PA-12 (Figure 3). This was demonstrated by the high initial TPH values registered in the PA-12 bays due to the degradation of their bitumen content. The BOF-slag sub-base was associated with high values of TPH (Figure 3) due to its chemical composition.

In summary, it was found that PMPC was the most efficient surface course in terms of improvement in water quality as is shown in Figures 2 and 3, followed by ICBP and PA-12. A sub-base of limestone aggregate presented the best performance in terms of pH, EC and TPH. However, BOF-slag showed the best performance in terms of TSS, turbidity and DO. Limestone aggregates can therefore be considered the best option for sub-base material across all water quality parameters.

3.2. Water quantity

Field tests undertaken using the LCS permeameter and the CP Infiltrometer in parking areas in Gijón and Santander demonstrated that PMPC surfaces showed the best infiltration performance, followed by ICBP and PA-12 as seen in Table 5. The CP Infiltrometer also showed that there was no generation of surface runoff under rainfall intensities of five minutes duration, corresponding to ten years (78 mm/h), fifty years (115 mm/h) and one hundred years (142 mm/h) in Gijón and ten years (98 mm/h), fifty years (155 mm/h) and one hundred years (178 mm/h) in Santander over the ICBP and PA-12 surfaces. However, the reinforced grass with plastic cells did generate a small amount of surface runoff (see Table 5).

Table 5. Average permeability measurements obtained with the LCS permeameter and height of inundation values obtained with the CP Infiltrometer.

Pervious Surface	Site (number of car park bays)	LCS		CP Infiltrometer (cm)		
		Time (s)	Permeability (m/s)	T=10 year	T=50 year	T=100 year
ICBP	"La Guía" (15 bays)	—	—	0	0	0
PA-12		21	0.0119	0	0	0
GRPC		—	—	0.6	0.6	1.0
ICBP	"Las Llamas" (45 bays)	—	—	0	0	0
PA-12		21	0.0119	0	0	0
PMPC		19	0.0132	0	0	0
GRPC		—	—	0.45	0.5	1.1
ICBP	"Parque Tecnológico" (8 bays)	—	—	—	—	—
PA-12		21	0.0119	—	—	—

4. CONCLUSIONS

The results of the three PPS field studies have been statistically analyzed, demonstrating important correlations between the sub-base materials (limestone aggregates and BOF-slag) and outflow water quality parameters: pH, DO, EC, TSS, turbidity and TPH. Limestone aggregates performed better than BOF-slag in terms of water quality, especially pH, EC and TPH.

A Spearman Correlation test accompanied by significance tests (Mann-Whitney and Kruskal Wallis) demonstrated that surface materials (PMPC, ICBP, PA-12, GRCC and GRPC) had a statistically significant influence on effluent water quality in terms of pH, TSS, Turbidity and TPH. However, this significance was not demonstrated for DO or

EC. The surface utilising PMPC was slightly better in terms of water quality and quantity, according to the parameters analyzed in this paper. However, it was found that the difference with ICBP and PA-12 was not significant.

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