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EFFECTS OF A POROUS PAVEMENT WITH RESERVOIR STRUCTURE ON RUNOFF WATER: WATER QUALITY AND FATE OF HEAVY METALS

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ABSTRACT

The present paper reports a study conducted to compare pollutant loading of runoff waters either collected at the outlet of a porous pavement with reservoir structure or coming from a nearby catchment drained by a conventional separate sewerage system, on the experimental site of Rezé (France). The mean pollutant loads measured at the reservoir structure appear notably lower than those measured at the reference catchment. A sampling operation of materials carried out in the porous pavement have confirmed the accumulation of metals in the porous asphalt and the absence of soil contamination under the reservoir structure. An attempt at mass balance for heavy metal distribution into the reservoir structure was made. The amount of metal evacuated at the outlet of the reservoir structure is generally low. Lead is mainly retained by clogging particles and between 57 and 85% of Cu, Cd and Zn are evacuated in the infiltrated water. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Heavy metal; infiltration; pollution; porous pavement; runoff.

INTRODUCTION

To face the urgent hydrological and environment quality preservation issues initiated by stormwater runoff in urban areas, new technical solutions to intensify the action of traditional urban storm drainage are now absolutely necessary. Porous pavements with reservoir structures, which have been developed to reduce runoff flow rates and volumes in strongly impermeable urban areas, seem to provide a satisfactory alternative for storm water treatment. Yet, the pollution reduction process taking place within these structures is relatively unknown (Pratt *et al.*, 1989; Hogland *et al.*, 1990; Legret *et al.*, 1994).

In order to study the impact of reservoir structure on the quality of both runoff water and soil, an experimental site was built up in 1991 in the city of Rezé, a town south of Nantes (Loire-Atlantique, France) (Raimbault and Métois, 1992).

Previous studies (Legret *et al.*, 1996; Colandini and Legret, 1996) concerned with about thirty rain events and comparing runoff water mean pollutant concentrations at the outlets of the reservoir structure and of a nearby reference catchment drained by a separate sewer system have shown that the pollution level of such a catchment is rather low and further that runoff water having gone through the porous pavement is notably less loaded than that coming from the nearby separate system. The reductions of suspended solid and lead concentrations were 64% and 79% respectively, and 72% and 67% respectively for zinc and cadmium. Analyses carried out on materials taken in 1992 from the reservoir structure and the soil underneath showed that heavy metals (lead, copper, cadmium and zinc) accumulate, for the most part, on the surface of the pervious asphalt and, for a small part, at the level of the geotextile separating the reservoir structure from the soil, which did not appear significantly contaminated after the four-year period during which the structure has been in operation.

In order to assess the effect of porous pavements on runoff waters better, the comparison of the quality of these waters developed by the authors considering pollutant loads exclusively is described here. New samples have been taken from the reservoir structure and the current distribution of heavy metals within the structure after a seven-year period in service has been assessed.

MATERIALS AND METHODS

Experimental site

The experimental site mentioned above consists of the catchment of the Classerie street drained by a reservoir structure, on the one hand, and of the reference catchment of the Le Praud housing estate drained by a separate sewer system, on the other hand. The reservoir structure was installed in 1988 during the repairing of the Classerie street over a 700 m section.

The street structure is made up of:

- a woven geotextile laid on the formation level;
- a 35 cm thick layer of 10/80 mm crushed material;
- two 10 cm thick layers of porous bituminous-bound graded aggregates;
- a 6 cm thick layer of 0/14 mm pervious asphalt with a 3/10 mm discontinuity

The side parking zones and the sidewalks are made up of 10/80 mm crushed material and pervious asphalt. Runoff water disposal is operated either by ground infiltration or by an outlet into a drainage pipe. The studied drained length of the structure is 255 m long; the contribution area is 2800 m^2, which corresponds to the surfaces of both the pavement and the sidewalks (2300 m^2) and to the connected roofs and impermeable areas (500 m^2). Storm water sampling is carried out with a glass bottle that is used to collect the first 10 litres of runoff water flowing through the outlet. The Le Praud reference catchment is located within one kilometre of the Classerie street and covers a surface area of 4.6 ha. The impermeability coefficient is assumed to be 0.43, which corresponds to a 2-ha impermeable area. Nonetheless, the actual impermeable surface area connected to the system studied is 1.7 ha. Runoff water samples have been taken at the outlet by a flowmeter-controlled automatic sampler.

Soil and water analyses

All soil and water analyses are carried out in accordance with the standard methods. In the water, total heavy metals (Pb, Cu, Cd and Zn) are determined by graphite furnace atomic absorption spectrometry (VARIAN SPECTRAA300) after raw waters have been acidified at pH lower than 2 with nitric acid and filtered through a 0.45 µm porosity membrane. Material and soil samples are sieved through nylon sieves to collect the 2 mm fractions and air dried. Volatile matter content (V.M.) is determined by measuring the loss of weight of the dried samples after they have been ashed at 550°C for 2 hours. Heavy metals are measured out by graphite furnace or flame atomic absorption spectrometry depending on the concentrations after the samples have been ashed at 550°C and the residue dissolved in a mixture of hydrochloric and hydrofluoric acids. The purity of the chemical products is recognized and the ultra pure water used has been deionised using an ion exchange column (MAXY). All glassware in contact with the samples is washed with nitric acid and rinsed out with demineralised water.

RESULTS AND DISCUSSION

Comparison of pollution loads contained in runoff waters

The global pollutant loading drained off downstream from both catchments is obtained by multiplying the volumes discharged by each catchment by the pollutant concentrations measured during each event. The data at our disposal come from a data base including about forty analyzed rain events, which has been developed from the results of the 4-year water quality survey (1991-1994) carried out on the Rezé experimental site.

However, it should be noted that all rain events do not systematically produce water flows at the outlet of the reservoir structure, water being sometimes retained by the aggregates, evaporating or infiltrating in the soil below the reservoir structure. On average, 96.7% of the storm water volume is considered to infiltrate in the soil below the reservoir structure (Colandini, 1997). Only the rain events, for which sampling was carried out simultaneously downstream of both catchments, have been taken into account here. Hydrological characteristics as well as suspended solid and heavy metal concentrations measured during these events are presented in Table 1.

Table 1. Characteristics of the events studied

	Reference catchment						**Porous pavement**					
Rainfall	**Volume**	**SS.**	**Pb**	**Cu**	**Cd**	**Zn**	**Volume**	**SS.**	**Pb**	**Cu**	**Cd**	**Zn**
(mm)	(m3)	(mg/l)	((µg/l)				(m3)	(mg/l)	(µg/l)			
49.3	560	44.3	23.4	6.0	0.33	136	4.2	42.5	7.2	7.9	0.10	-
25.6	430	6.7	13.2	4.5	1.54	177	0.2	3.8	2.0	5.9	0.70	30.1
16.6	322	33.0	16.4	5.8	0.80	180	0.3	8.2	3.2	6.8	0.01	180
12.7	448	7.0	7.1	44.1	1.34	154	0.2	2.5	3.2	4.5	0.30	66
32.1	403	8.7	8.7	11.4	0.92	226	0.5	3.4	1.5	19.6	0.04	51
21.4	395	73.3	26.2	8.7	1.61	154	0	2.7	1.3	8.2	0.35	31
39.8	470	23.0	15.8	13.2	1.85	138	0.7	5.4	0.6	8.1	0.69	8
36.2	581	25.0	14.3	8.5	1.19	130	3.5	2.1	1.6	4.4	0.08	17
34.0	450	5.0	63.1	5.7	0.80	131	0.7	2.8	0.5	3.5	0.16	17
50.7	513	86.1	24.2	8.9	2.93	194	8.6	7.6	1.7	9.9	0.05	26
52.1	435	32.7	15.5	6.7	0.86	120	0.2	11.1	3.9	12.1	0.24	30

Regarding the reference catchment, we consider that only the impermeable areas connected to this catchment contribute to storm water runoff. Regarding the catchment of the porous pavement with reservoir structure, we consider that, for each rain event, the pollution loading is the result of the sum of the loads drained off into the main sewer and of the loads infiltrated into the soil below the structure. Given that no results on the infiltration phenomenon are available, the infiltrated volume is assumed to be the difference between storm water and runoff water volumes measured on the site. Finally, the infiltrated water is taken to be of the same quality as that of the sampling bottle.

The comparison between the pollution loads drained off per hectare of contribution area downstream of the two catchments is presented in Table 2. The efficiency of the reservoir structure is determined in relation to the loads obtained on the reference catchment.

Table 2. Comparison between event pollutant loadings

	SS. (kg/ha)	Pb	Cu (g/ha)	Cd	Zn
Porous pavement					
Minimum	0.32	0.17	0.57	0.001	3.2
Maximum	20.9	3.6	6.3	0.27	29.9
Mean	3.5	0.88	3.0	0.08	11.3
Standard Dev.	6.0	1.0	2.1	0.08	8.2
Reference catchment					
Minimum	1.3	1.9	1.1	0.11	34.1
Maximum	26.0	16.7	11.6	0.88	58.5
Mean	8.5	5.6	3.0	0.35	41.8
Standard Dev.	7.8	4.2	3.0	0.22	8.5
Mean difference (%)	**59**	**84**	**-**	**77**	**73**

Pollutant loads found in the literature addressing the problem of storm water runoff downstream of conventional separate sewer systems are generally higher than the loads obtained on the Rezé experimental site. Storm water pollutant loads at the outlet of conventional sewer systems are estimated to range between 1,000 and 2,000 kg of suspended solids per impermeable hectare per year and between 0.7 to 2.2 kg of Pb per impermeable hectare per year (Chocat, 1997). Considering the mean annual pluviometry in Rezé to be 787 mm (mean value obtained between 1961 and 1990), pollutant loads drained off by the storm waters of the reference catchment total 200 kg of suspended solids and 0.130 kg of Pb per impermeable hectare per year. Although the level of contamination of the water flows at the outlets of the two catchments in Rezé are comparatively low, the suspended solid and heavy metal concentrations (with the exception of copper, for which the difference is not significant) drained off by the porous pavement with reservoir structure are lower than the loads obtained on the reference catchment. The efficiency of the porous pavement highlighted through the rain events studied agrees with the efficiency level determined from the concentration means obtained for all the flows analyzed during the measurement campaign.

Location and distribution of heavy metal flows within the reservoir structure

The first in-situ examination of the Rezé experimental structure was carried out in 1992 (Legret *et al.*, 1996) and in 1996, a second trench, about 1.20 m wide and 9 m long, has been cut across the street. Three vertical profiles were made to collect the following samples:

- Clogging particles: consist of the sediments found within the pores of the pavement surfacing, which have been isolated by manually separating the aggregates from the asphalt sample, then washing them up with demineralised water and finally, sorting and eliminating them through a 5,000 µm sieve.
- Crushed material: although the pavement constituent aggregates did not reveal any visible layer of sediment, some sediment samples were obtained by washing the aggregates with demineralised water (about 10 kg) and screening the suspension through a 5,000 µm sieve to separate the aggregates from the sediments.
- Geotextile: the sediment particles having accumulated at the level of the geotextile have been collected by washing the three geotextile samples with demineralised water, then screening through a 5,000 µm sieve to eliminate the floating geotextile fibers.
- Soil: sampling under the pavement structure was carried out up to 142 cm deep.

Table 3 illustrates the results of the analyses.

Furthermore, by the end of 1994, the permeability of the pavement surfacing proving inadequate, a first cleaning operation was carried out in November 94 with a road suction sweeper consisting in sweeping, then spraying water under pressure (120 bars) on the surfacing and finally sucking up the resulting sludge. This first campaign was followed by a second cleaning operation in June 1995 with a more powerful device specially designed for porous asphalt maintenance and combining high-pressure rotary spraying and suction (spraying of 400-bar high pressure water on the pavement followed immediately after by the suction of the resulting sludge). The infiltration capacity of the porous surfacing was significantly improved after the maintenance operation. The results of the sludge analyses also appear in Table 3.

Table 3. Heavy metal concentrations in the porous pavement (<2mm fraction)

	Sample	< 125 µm	VM.	Pb	Cu	Cd	Zn
		(%)	(%)	(mg/kg)			
1992 Sampling	Geotextile	30	2.6	69	23	0.27	191
	Soil (61-75cm)	44	3.8	50	15	0.11	97
	Soil (75-85cm)	50	4.3	43	15	0.08	91
	Soil (85-110)	42	4.5	47	14	0.04	108
	Soil (110-150cm)	35	3.1	29	15	0.08	111
1996 Sampling	Clogging part.	59	9.0	447	67	1.11	315
	Crushed mater.	30	1.7	61	16	0.12	76
	Geotextile	56	3.3	46	16	0.10	81
	Soil (61-62cm)	55	2.7	41	15	0.07	63
	Soil (62-72cm)	48	3.4	36	12	0.05	62
	Soil (72-82cm)	58	4.2	29	15	0.12	81
	Soil (82-92cm)	48	3.7	31	12	0.04	71
	Soil (92-102cm)	37	3.6	24	25	0.24	84
	Soil (102-112cm)	34	3.2	24	15	0.06	76
	Soil (112-122cm)	35	3.7	23	16	0.06	87
	Soil (122-142cm)	34	3.5	22	18	0.05	99
Reference soil	Soil (60-80cm)	54	3.0	39	11	0.08	111
	Soil (80-100cm)	43	3.3	37	11	0.07	135
	Soil (100-120cm)	45	2.8	34	12	0.06	151
Clogging particles	94 Nov.	17	1.6	154	46	0.23	334
	95 June	48	12.8	427	78	1.01	339

Most of the metal contamination on the site is located in the porous surfacing. The infiltration of storm waters into the porous asphalt over a more than 8-year period did not cause any migration of the particulate metallic pollution within the reservoir structure.

During the studies conducted to examine clogging mechanisms, Pichon (1993) had observed that the loss of permeability of the porous asphalt resulted from the densification of the particles retained in the surfacing and not from the propagation of the clogging particle front trapped within the asphalt. The level of contamination of the clogging sediment is high compared with the other samples. The comparison of the concentrations in both cleaned resulting sludge samples leads one to suppose that heavy metal contamination is all the higher since the fine particle proportion is considerable and the sample is organic.

The porous layers under the surfacing have a minor effect on the retention of the particulate pollution. However, during the examination of 1992, we had observed that our sediment sample from the structure base geotextile was slightly contaminated, a contamination which did not appear during the 1996 examination. The 1992 examination, we realized, was carried out near a roof runoff water entry and the introduction of the water into the reservoir through drains and not by infiltration into the porous surfacing may account for the slight accumulation of contaminated sediments at the level of the geotextile close by and for the fact that it did not appear during the 1996 examination. Lastly, we notice that heavy metal concentrations in the soil under the porous pavement structure are comparable to those obtained in the reference samples taken in proximity to the experimental site.

To complete the study, a second approach was considered consisting in the evaluation of the mass balance for heavy metal distribution within the reservoir structure after a 7-year period in operation (between 1988 and 1995). Calculations rest on the metal concentrations measured in the clogging materials of the porous asphalt (sampling of 1994 and 1995) and in the water sample taken at the outlet with the 10-liter bottle. These data (Colandini, 1997) are:

- volume of infiltrated water: 96.7% of the volume of the precipitations
- mean annual pluviometry: 787 mm
- heavy metal mean concentrations of water at the outlet of the pavement:

Pb = 3.7 µg/l - Cu = 8.7/µg/l - Cd = 0.5 g/l - Zn = 52 µg/l

- mass of dry materials clogging the porous asphalt: 0,20 kg/m^2 in 1994 (among which 77.3% of the particles are smaller than 2 mm) and 0.53 kg/m in 1995 (among which 79.2% of the particles are smaller than 2 mm). The metal concentrations of these materials are detailed in Table 3.

The results are displayed in Figure 1.

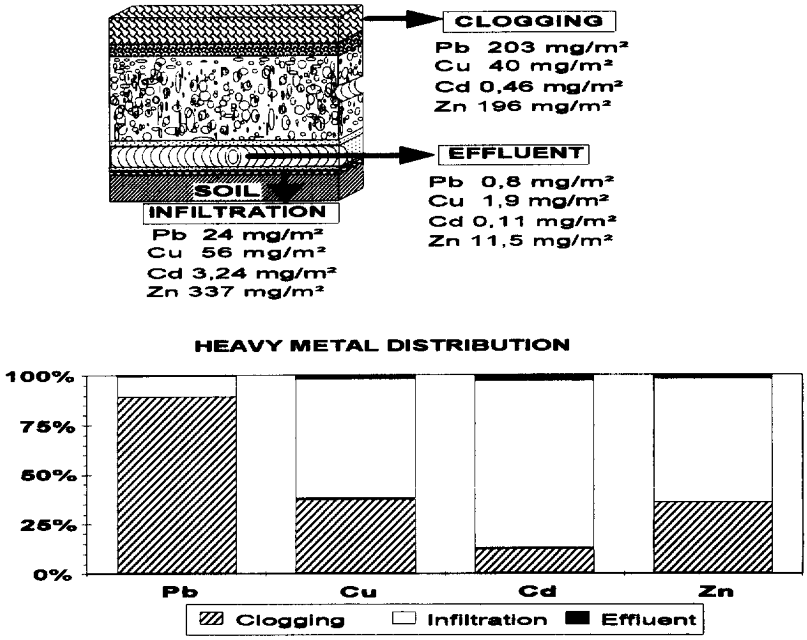

Figure 1. Mass balance and distribution of heavy metals in the structure (7 years).

From such an approach, the porous pavement in Rezé proves perfectly efficient to trap particulate pollution of storm waters. A considerable proportion of lead, in particular, which is mainly conveyed by suspended solids, is retained in the porous surfacing of the pavement. Heavy metals in soluble form (copper, cadmium and zinc) are retained to a lesser degree in the reservoir structure and, following the course of the water, they infiltrate the soil under the structure. During both examinations, no trace of pollutant accumulation was revealed in the soil because of the very low level of contamination of the storm waters coming from the pavement. Assuming the accumulation of heavy metals on a 2-cm thick layer of soil with a density of 1.6, it appears that the increase in the metal concentrations after a 7-year period would be 0.75 mg/kg for Pb, 1.8 mg/kg for Cu, 0.1 mg/kg for Cd and 10.5 mg/kg for Zn respectively.

CONCLUSION

The comparison between pollution loads (SS, Pb, Cu, Cd and Zn) in storm waters at the outlets of both a porous pavement with reservoir structure and a nearby catchment drained by a separate sewer system demonstrates that the quality of the waters is significantly improved by the passage through the porous pavement. These results confirm those obtained previously by the comparison of pollutant concentrations in runoff waters.

Moreover, further samples taken from both the structure and the soil underneath show that metallic pollutants are mainly retained in the porous asphalt and that the soil under the structure does not present any significant contamination after the 8-year period during which the pavement has been in operation.

Lastly, the attempt to evaluate heavy metal distribution between clogging materials, infiltrated waters and effluents has revealed that the porous pavement is particularly efficient in the retention of lead associated with suspended solids in the porous asphalt, whereas zinc, copper and cadmium seem to be evacuated by infiltration under the pavement structure.

Although metal flows appear weak, we now need to resort to mathematical models to obtain further information in order to improve our understanding of the long-term metal migration within this type of structure.

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