The clogging behaviour and treatment efficiency of a range of porous pavements

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ABSTRACT

This paper presents the findings of a laboratory investigation into the clogging behaviour of three different porous pavements that were most representative of the available range and their pollutant removal efficiency over time. These pavements were monolithic Porous Asphalt (PA), Permapave (PP), and modular Hydrapave (HP).

The pavements were dosed with a semi-synthetic stormwater mixture over a continuous period of 20 weeks, at a flow rate of 3.9 mm/hr, the intensity of which corresponds to the 90th percentile of an average recurrence interval (ARI) storm in Melbourne or the mean of an ARI storm in Brisbane, Australia. Inflow and outflow samples were collected and analysed for key pollutants such as total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), heavy metals and dissolved nutrients. Flow rates, pH and temperature readings were also measured. A 1 in 5 year Brisbane storm, which is equivalent to more than a 1 in 100 year Melbourne storm was simulated in the 6th, 10th and 17th weeks to evaluate the rate of clogging; this corresponded to 5.5, 10.4 and 17.5 years of operation in Melbourne, or about half these periods in Brisbane.

Under normal dosing, all three systems were capable of removing approximately 100% of TSS, 30% of TP and 20% of TN after 17 years of operation, with no large differences between the systems. For the 'average' conditions, none of the pavements showed signs of clogging even after 17 years of operation in Melbourne or 8.5 years in Brisbane. However, for the flooding conditions, HP started to pond after 5.5 years in Melbourne (or less than 3 years in Brisbane), while PA showed signs of clogging after 10.4 years in Melbourne (5.2 years in Brisbane). However, Permapave has still not showed signs of clogging after 17 years of operation in Melbourne, even for a 1 in 100 year event.

KEYWORDS

stormwater management, porous pavement, clogging, pollutant removal, flooding, laboratory study

INTRODUCTION

With urban runoff being one of the major causes of pollution, stormwater management is becoming a high priority. Most of the available stormwater management measures are difficult to implement on a wide scale due to infrastructure and space/cost constraints, with porous pavements providing one technique, which can be retrofitted easily within developed urban areas (Newton *et al.*, 2003). To enhance their structural performance and reduce costs, they are often combined with non-permeable surfaces to cover only a certain percentage, rather than the whole catchment.

Porous pavements, as their name implies, are a pavement type that promote infiltration, either to the underlying soils, or to a storage reservoir below them. They come in several forms and are either monolithic or modular. Monolithic structures consist of bound granular material, without the finer aggregate grain sizes, while modular structures are constructed from individual pavers, with a gap in between each paver. They are usually laid on sand or fine gravel underlain by a layer of geotextile, with a layer of coarse aggregate below. Geotextile mitigates the migration of fines from the underlying sub-grade into the sub-base layer (Ferguson, 2005).

The ability of porous pavements to reduce peak flood discharges and reduce runoff volume by infiltration to the underlying soil are the major reasons for their adoption in many countries (Scholz and Grabowiecki, 2007). The efficiency of porous pavement in attenuating peak discharges has also been confirmed in several studies (Pratt *et al.*, 1999; Bean *et al.*, 2007). However, a lack of information on the treatment performance and clogging behaviour is one factor impeding their adoption. Clogging is a process that develops over time, due to the accumulation and deposition of sediments from stormwater (Bouwer, 2002). This process decreases the porosity, permeability and hence the infiltration rate of a system. Siriwardene *et al.* (2007) studied physical clogging and found that a clogging layer forms at the interface between the filter and underlying soil, and that the main driver in the development of clogging layer is the migration of particles less than 6 microns in diameter.

Although a lot is known about the pollutant removal performance of porous pavement (Booth and Leavitt, 1999), particularly when the system is 'new', very few studies have been published, which address clogging and its impacts on hydraulic behaviour, and how these phenomena respond to the effects of ageing. The key mechanisms that govern clogging in different systems are also poorly understood.

The aim of this project is to deliver new insights into the nature of porous pavement clogging and consequently the treatment performance of these systems under Australian conditions. This will be achieved by investigating the rate of clogging and the treatment efficiency of key stormwater pollutants. This paper reports on the first phase of a laboratory investigation into processes that occur within typical porous pavement systems (the case when pavements are used for attenuation of flow with no ex-filtration allowed).

METHODS

Three porous pavement systems that represent the available range were chosen in this study (Figure 1). They are the traditional monolithic porous asphalt (PA), popular modular Hydrapave (HP) (known as Formpave in the UK), and Permapave (PP), a new type of monolithic pavement developed in Australia. PA consists of a standard bituminous asphalt surface, in which all the fines have been removed, a filter layer of crushed aggregate, a reservoir layer and a layer of geomembrane (Diniz, 1980). HP is an 80 mm thick concrete paver with a unique chamber and bevel system, which is laid on a 50 mm course of 5 mm stone (Boral Clay and Concrete, 2005). The laying course is further separated from the upper and lower sub-base by a layer of geotextile. PP is made from crushed gravel of 50 mm thickness and is placed over a layer of 5-20 mm screen crushed rock (Dymon Industries, 2007).

This laboratory study was conducted in a compressed time scale, the wetting period of which has been exaggerated (with no drying cycle), in order to study the clogging processes, which normally occur over a number of years within a short time. The pavements were investigated for their rate of clogging as well as their treatment efficiency of key stormwater pollutants.

Laboratory Rig

The pavements were installed side by side in a 2.7 m x 0.45 m x 1.95 m rig, which was divided into three separate vertical compartments (Figure 1). HP and PP were installed according to the specifications supplied by their manufacturers, while PA was installed following the standard guidelines ((Boral Clay and Concrete, 2005; Dymon Industries, 2007). Since the aim was to investigate the processes within the systems only (rather than in underlying soils), all flow through the systems was collected by perforated pipes. The gravel, used as the sub-base for each system, was thoroughly washed prior to the filling of the rig to ensure that they were free of fines. Each sub-base layer was compacted with a hand tamper before the pavement was placed firmly over the sub-base. As the basis of operation for HP is the infiltration of water through the small channels formed at the end of the pavers, careful measurements were taken to maintain the ratio of channel to paver area (typical of normal installation) and the exact number of pavers and channels in the rig.

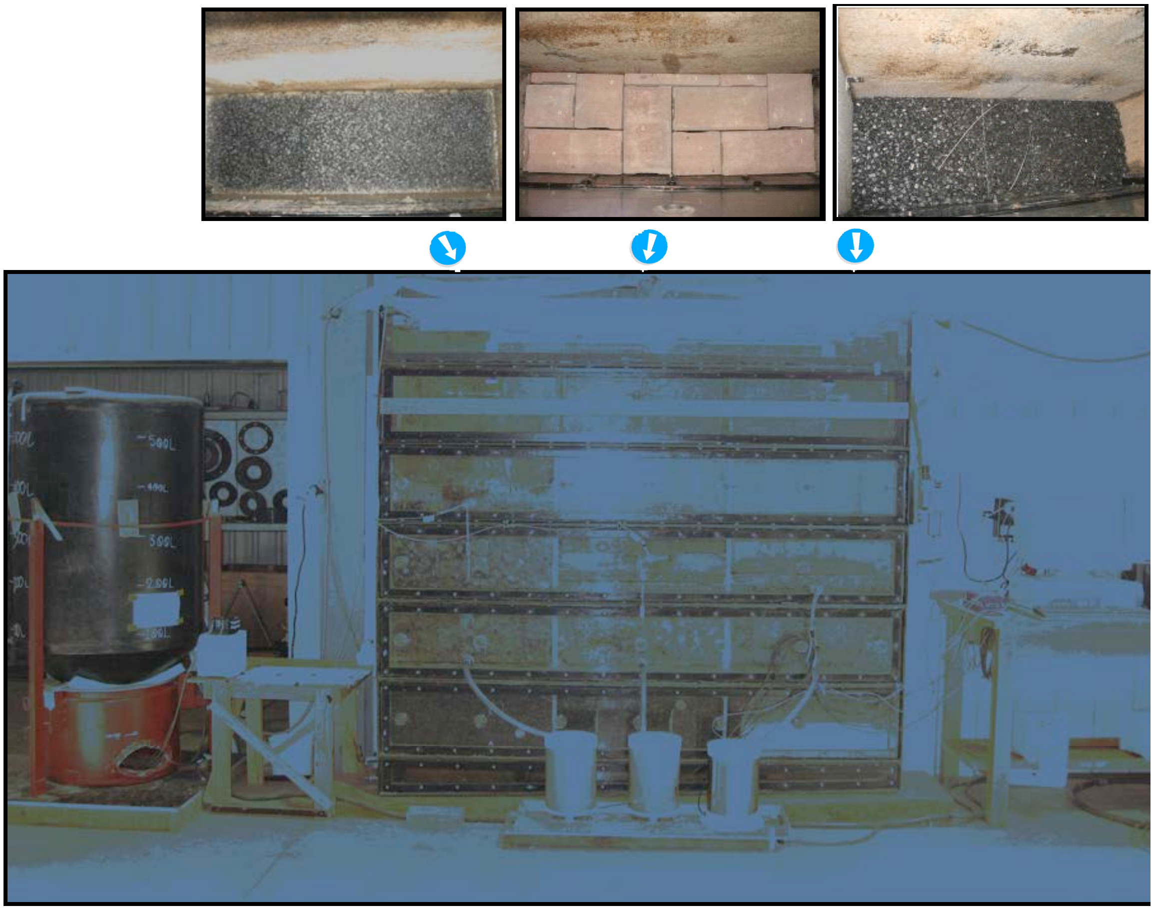

Figure 1.The experimental rig for the comparison of PA, HP and PP.

The stormwater distribution system consists of a 550 L tank, a peristaltic pump, connection tubes and a specially designed pneumatic water delivery mechanism that uniformly distributes stormwater over each surface. This distribution system was continually refined until the same uniform inflow of water was achieved over each of the porous pavement systems.

Experimental Procedure

Prior to the commencement of this experiment, a series of hydraulic conductivity tests was performed to determine the porosity of each individual pavement system when "new", using clean tap water. Standard Darcy's tests (water was fed from bottom-up) were carried out.

It was decided to conduct the study for typical inflow rates that are reflective of temperate Melbourne and sub-tropical Brisbane climates in order to cover a wide range of Australian conditions. These flow rates were determined using the Model for Urban Stormwater Improvement Conceptualization (MUSIC) (CRCCH, 2005). For this modeling exercise, an initial loss value was needed (i.e. the rainfall depth after which flow through the pavement will happen). Since no such data was available in the literature, the initial loss was measured in several controlled field tests. It was found that on average 0.85 mm was lost at the start of each event, before flow through PP was observed. Using this value as an input into MUSIC, the frequency curves of a typical 30 year "effective" rainfall event for both Melbourne and Brisbane were generated. From each of these curves, four different flow rates, corresponding to the mean, median, 90th and 99th percentile as shown in Tables 1 and 2, were chosen as suitable flow rates.

Table 1. Selection of flow rates from 30 year Melbourne Rainfall Time Series.

Frequency	Flow rate per ha.	Velocity		Pavement Area	Flow rate	
	m^3/sec	m/sec	mm/hr	m^2	m^3/sec	mL/sec
Median	0.0017	1.7E-07	0.6	0.1564	2.6E-08	0.026
Mean	0.0045	4.5E-07	1.6	0.1564	7.1E-08	0.071
90%	0.0108	1.1E-06	3.9	0.1564	1.7E-07	**0.169**
99%	0.0375	3.8E-06	13.5	0.1564	5.9E-07	0.587

Table 2. Selection of flow rates from 30 year Brisbane Rainfall Time Series

Frequency	Flow rate per ha.	Velocity		Pavement Area	Flow rate	
	m^3/sec	m/sec	mm/hr	m^2	m^3/sec	mL/sec
Median	0.0031	3.1E-07	1.1	0.1564	4.8E-08	0.048
Mean	0.0088	8.8E-07	3.2	0.1564	1.4E-08	**0.137**
90%	0.0208	2.1E-06	7.5	0.1564	3.3E-07	0.325
99%	0.0900	9.0E-06	32.4	0.1564	1.4E-07	1.400

For the initial stage of the study, the constant flow rate that corresponded to the intensity of the 90th percentile of the average recurrence interval (ARI) storm in Melbourne or the mean of the ARI storm in Brisbane was used. This corresponds to a flow of 3.9 mm/hr through each pavement system.

The pavements were subsequently dosed at this constant flow rate, with a semi-synthetic stormwater mixture. The stormwater was prepared by mixing sediment from a stormwater wetland with tap water in known volume, and topping up with specific concentrations of dissolved pollutants to achieve pollutant concentrations typical of urban land use, as shown in Table 3 (this method has previously been described by Hatt *et al*. (2007b)). The pneumatic water delivery system ensured the random and equal distribution of water as well as sediments over the three surfaces, to simulate 20 years of real life operation.

Table 3. Typical urban stormwater pollutant concentrations (Duncan, 1999).

Pollutant	Concentration (mg/L)
Total Suspended Solids (TSS)	150
Total Nitrogen (TN)	2.6
Total Phosphorus (TP)	0.35
Copper (Cu)	0.05
Lead (Pb)	0.14
Zinc (Zn)	0.25
Cadmium (Cd)	0.0045

At this stage of the project, there was no simulated drying phase, and the continuous delivery of stormwater over 1 week simulated approximately 1 year of average inflows into the system in Melbourne (650mm of rainfall per year) or 0.5 year of average inflows in Brisbane. Future stages will test the wetting and drying effects, and sequences of varying inflow rates, over longer timespans.

Sampling Procedure and Clogging Monitoring

An initial intensive sampling regime was conducted during the first two weeks to determine the required sampling frequency to detect statistically significant changes. This regime was subsequently reduced to three separate composite samples per week. While the first composite was collected every Monday, Wednesday and Friday, the second composite was collected every Friday and Monday, and they were both analyzed for TSS, TP and TN. A third composite was collected every fortnight on Wednesdays and analyzed for TSS, TP, TN, total dissolved nitrogen (TDN), filterable reactive phosphorus (FRP) as well as total and dissolved metals. The analytes were analyzed in accordance with standard methods for the examination of water and wastewater (APHA-AQQA-WPCF, 2005). Particle size distributions (PSD) were also measured in the samples that had sufficient sediment using a Beckham Coulter LS100Q Laser Diffraction Particle Size Analyser.

During each sampling session, samples were taken at both inflow and outflow. The flow rates, temperature and pressure in, and just underneath, each pavement were also monitored continuously as previously described by Siriwardene *et al*. (2007). The collection of every sample was accompanied by pH measurement to enable early predictions to be made about the behaviour of metals in the system. This approach was particularly beneficial as the turnaround time for the laboratory analyses of metals was approximately 3 months.

To study the rate of clogging during typical floods, a 1 in 5 year Brisbane storm (of 5 min. duration – typical design flood for small catchments where porous pavements are likely to be deployed), that is also equivalent to a more than 1 in 100 year Melbourne storm (of 5 min. duration), was simulated in each of the 6^{th}, 10^{th} and 17^{th} weeks of the experiment. The intensity of these storms was 191 mm/hr, which translates into a flow rate approximately 50 times higher than the average constant inflow into each system.

To date, around 20 years of operation in Melbourne climate have been simulated. The plan is to complete the experiment in the very near future and then dismantle the pavements. The mass of accumulated sediment and pollutants in the systems will also be measured.

RESULTS AND DISCUSSION

Hydraulic Conductivity of Clean Systems

A comparison of the three systems shows that PP is the most porous system as a whole, while the HP bricks have the highest infiltration capacity, as shown in Table 4. This was not surprising, as water can seep freely through the channels on the sides of the modular pavements. The sub-bases of all three systems have a similar infiltration capacity, with the railway ballast sub-base of PA being the most porous. The limiting layer for PA was the pavement surface, which was 10 times less porous than its sub-base. Conversely, HP was limited by its sub-base, while its pavers were highly porous (by a factor of more than 10). Once again, this was not surprising, as the HP sub-base contained a geotextile layer, which acted as the "choking" element. PP has a surface that is 4 times more porous than its sub-base. Although the PP surface and sub-base were constructed from similar sized aggregates, these results suggest that this aggregate in the sub-base was less uniformly distributed.

Table 4. The hydraulic conductivities of the overall system (k_e), pavement (k_p) and sub-base (k_b) obtained for PA, HP and PP from the two experiments.

Pavement Type		k_e (m/d)	k_p (m/d)	k_b (m/d)
PA	Average	544.3	101.7	1188.6
	Std. dev.	15.9	8.9	110.6
	S.E.	5.0	2.8	35.0
HP	Average	564.9	5156.1	485.5
	Std. dev.	13.5	7573.4	12.0
	S.E.	3.7	2100.5	3.3
PP	Average	810.0	2888.8	734.5
	Std. dev.	6.9	24.5	6.2
	S.E.	1.9	6.8	1.7

Clogging Development

Table 5 presents results on ponding in each of the three systems during the average constant inflow, as well as during the 3 simulated storms.

Table 5. Depth of Ponding Layer Observed over Time

Duration	Ponding depth indicating clogging (mm)		
	PA (above pavement)	HP (above geotextile)	PP (above pavement)
1 week – average rainfall	0	0	0
5 weeks – average rainfall	0	0	0
5.5 weeks – Flood Storm 1	***0***	***0***	***0***
10 weeks – average rainfall	0	0	0
10.4 weeks– Flood Storm 2	***0***	***60***	***0***
15 weeks – average rainfall	0	0	0
17.5 weeks – Flood Storm 3	***2***	***110***	***0***

Nb: 1 week of inflow corresponds to 1 and 0.5 years of operation in Melbourne and Brisbane, respectively.

In the first ten weeks of running the 90th percentile Melbourne rainfall, manual flow measurements of the inflow and outflow showed no losses in infiltration capacity. In fact, even the introduction of the 1 in 5 year Brisbane storm (in the 6th week) showed no ponding in all three systems, as shown in Table 5. However, upon the simulation of the 2nd storm event (in the 10th week), a ponding layer of approximately 60 mm was observed, only for HP, above the geotextile layer. This ponding layer of 60 mm reached approximately half the height of the HP pavements, but did not reach the surface of the pavements. In the 3rd simulated storm event (in the 17th week), the ponding layer in HP reached 110 mm above the geotextile, while PA recorded a ponding layer of approximately 2 mm. The observation of ponding in both the 2nd and 3rd storm events, was accompanied by elevated pressure readings as well as outflow from the sampling port for HP. Clogging appeared to be occurring on the geotextile surface and the channels located at the ends of the pavers. This was clear evidence of clogging in HP and PA during the storm simulations in the 10th and 17th week of operation.

It can be concluded that after 17 years of continuous operation in Melbourne, PP is the only system that can cope with a 1 in 100 year event, and that after 8.5 years in Brisbane, it can cope with a 1 in 5 year storm. At the same time, PA would start to experience some clogging problems towards the end of this period, and HP would fail to cope with flooding conditions.

Pollutant Removal

The average inflow concentration across all three pavements for each key pollutant (TSS, TP and TN) and their individual removal percentages from both the normal dosing and two storm events are summarized in Table 6.

Table 6. Average TSS, TP and TN Inflow Concentrations and their Removal Percentages over Time

Duration	TSS				TP				TN			
	Ave. Inflow (mg/L)	Removal %			Ave. Inflow (mg/L)	Removal %			Ave. Inflow (mg/L)	Removal %		
		PA	HP	PP		PA	HP	PP		PA	HP	PP
1 year	217	99	99	99	0.59	80	86	82	3.37	51	54	52
5 years	271	99	100	100	0.65	69	75	71	3.62	37	30	28
5.5 years (Storm 1)	111	65	86	76	0.49	28	38	29	2.87	14	18	17
10 years	127	99	100	98	0.47	66	75	68	2.75	34	24	25
15 years	138	99	99	99	0.57	61	73	67	3.10	40	27	27
17.5 years (Storm 3)	159	79	94	85	0.59	28	43	33	3.10	16	29	23

TSS: The average inflow concentration for all three pavements ranged from 100 to 300 mg/L throughout the experiment (Table 6 and Figure 2). The PSD analyses of TSS inflows showed that the median particle diameter was 26 microns, which is typical of stormwater inflows (Deletic and Orr, 2003). Despite the variable inflow concentrations, the average outflow concentration recorded for all three pavements remained quite constant at less than 5 mg/L. This low outflow concentration indicates a removal rate of close to 100%, even after 17 years of simulated operation (Figure 3). However, simulation of the 1st and 3rd storm events (no data were collected for the 2nd event) showed a decreased removal for all systems. When the flow rate was increased 50 times, TSS removal decreased to 65-80% for PA and 75-85% for PP. The geotextile layer in the HP sub-base allowed this system to maintain a removal of >85%. Whilst these findings indicate the importance of flow rate on the treatment performance, it is encouraging that even during large flood events, the systems were able to achieve a high removal rate of solids.

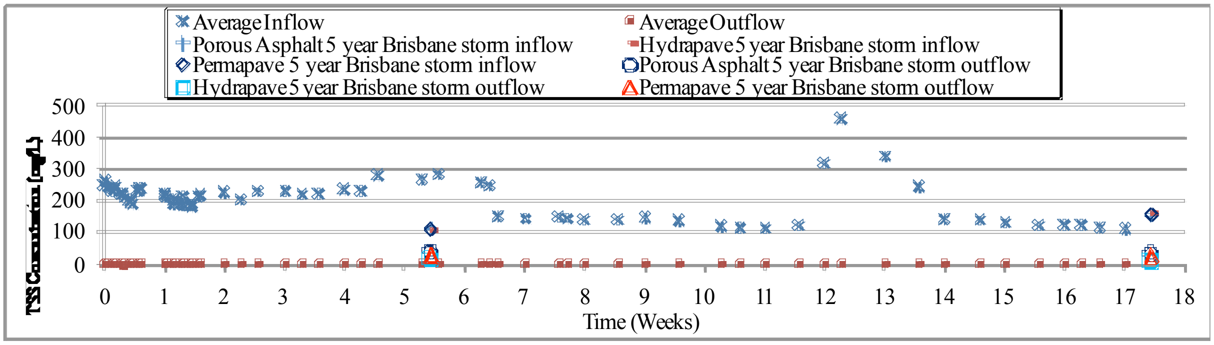

Figure 2. Graph Showing the Inflow and Outflow Concentrations (mg/L) of TSS, measured on a Daily and Composite Basis for PA, HP and PP.

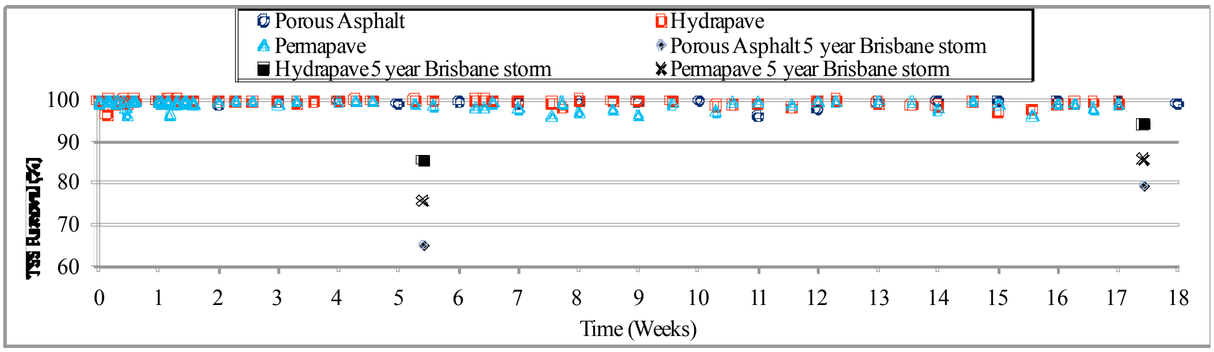

Figure 3. Graph Showing the Removal Percentage of TSS, measured on a Daily and Composite Basis for PA, HP and PP.

TP: Throughout the experiment, the inflow and outflow concentration remained fairly steady around 0.57 mg/L and 0.17 mg/L respectively (Table 6), with slightly lower outflows recorded in the first week of experiment (Figure 4). At the start of the experiment, all three pavements had a removal rate of approximately 80%, dropping to 60% after 17 years.

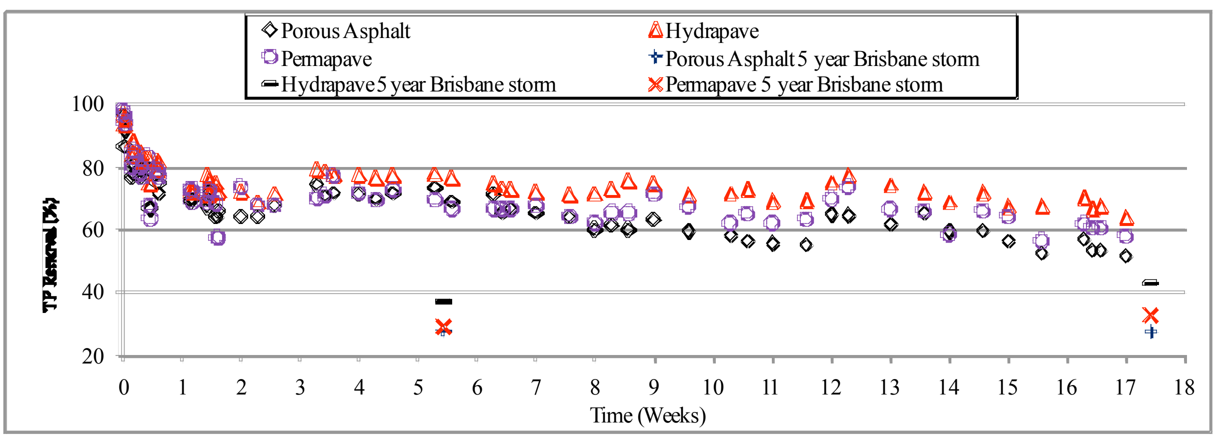

Figure 4. Graph Showing the Removal Percentage of TP, measured on a Daily and Composite Basis for PA, HP and PP.

However, results from the storm events in the 6th and 17th week showed a drop in removal percentage to approximately 30%, with HP performing slightly better than PA and PP (Figure 4). As most phosphorus compounds in the inflow are particulate bound, the removal of sediments is also responsible for most of the P removal, thus indicating that the three pavements are efficient in removing not only TSS but TP as well.

TN: The TN inflow concentrations remained fairly constant at approximately 3 mg/L (Table 6). Within the first week, the average TN removal recorded was approximately 50%, as shown in Figure 5. After only 2 weeks, this value dropped down to approximately 30% and stayed rather constant for the next 15 weeks. The simulation of storm events in the 6th and 17th week saw a decrease to approximately 20%. TDN analyses of the inflow and outflow samples show that approximately 70% of the TN species in the introduced stormwater is in the dissolved form, and that there is almost no removal of TDN through the pavements. The systems are however, moderately efficient in removing particulate bound nitrogen, as shown by Hatt *et al.* (2007b), who found that gravel filters were less effective at nitrogen removal, particularly for dissolved nutrients. There was no leaching of nitrogen, which was rather surprising and contrary to the findings by Hatt *et al.* (2007a) who found that stormwater gravel filters will start leaching TN over time. The lack of a drying and wetting regime may explain this behaviour. Drying could play an important role in the process of TN removal as shown in a study of fine stormwater filters by Hatt *et al.* (2007a).

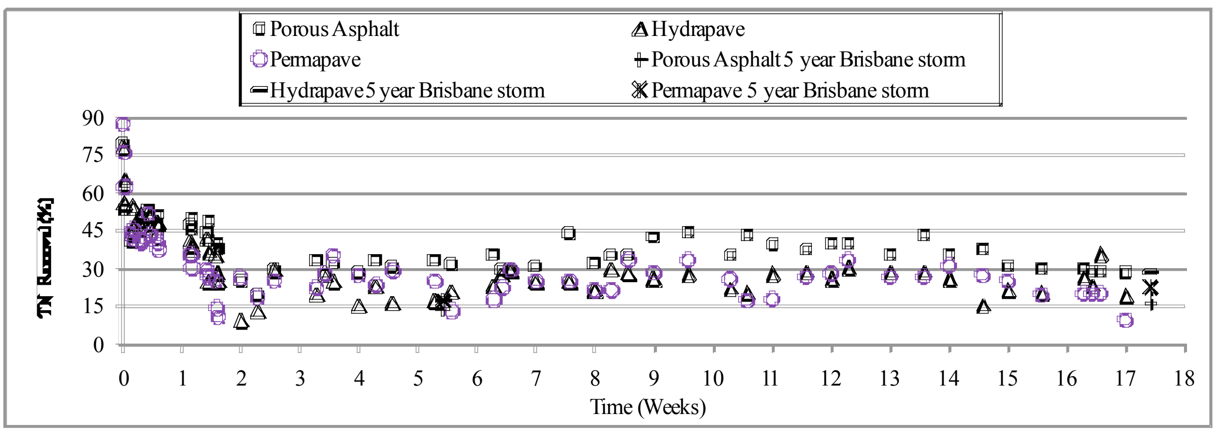

Figure 5. Graph Showing the Removal Percentage of TN, measured on a Daily and Composite Basis for PA, HP and PP.

CONCLUSIONS

In this study of 3 representative porous paving systems, it was found that modular Hydrapave was the most likely to clog first; ponding will start to occur during flood events after 5 and 10 years of its operation in Brisbane and Melbourne respectively. The most likely reason for Hydrapave showing the worst performance is the presence of the geotextile layer in its sub-base. Porous Asphalt will start to pond after 8.5 and 17 years of operation in Melbourne and Brisbane respectively. After 17 years of operation, Permapave is the only system that has yet to show signs of clogging. The observations also suggest that all three studied systems are capable of continually handling average rainfall events.

Over time and for constant average inflows, all 3 pavements demonstrated TSS removal rates of close to 100%, but showed lesser removal efficiencies for TP (30%) and TN (20%). Hydrapave appeared to be slightly more efficient in removing TSS and TP (probably due to its geotextile layer), while TN removal was similar in all three pavements. It is interesting that the removal of TSS and TP decreased during flood events, suggesting that flow rate is an important factor in the particulate removal process. However the flow rate did not play a big role in the removal of TN, which was predominantly in the dissolved form. The results on TN removal should be considered with caution as these experiments did not simulate drying periods that occur in reality, and have been shown to affect TN removal and leaching (Hatt *et al.*, 2007a).

The next stage of this experiment will simulate varied inflows to mimic natural rainfall frequency. Five flow rates will be randomly applied, each representing 1/5 of the rainfall distribution curve for Brisbane. Drying cycles will also be simulated in between the wet periods using a drying lamp.

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