Pollutant load removal efficiency of pervious pavements: is clogging an issue?
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ABSTRACT
Pervious pavements in car parks and driveways reduce the peak runoff rate and the quantity of runoff discharged into urban drains as well as improve the stormwater quality by trapping the sediments in the infiltrated water. The paper focuses on presenting results from the laboratory tests carried out to evaluate water quality improvements and effects of long-term decrease in infiltration rates with time due to sediments trapping (clogging) within the pavement pores. Clogging was not found to be a major factor affecting pervious pavement performance after simulating 17 years of stormwater quality samples.

Key words | pervious pavement clogging, pervious pavements, stormwater infiltration, WSUD

INTRODUCTION
Water Sensitive Urban Design (WSUD) is a technique that has emerged throughout the world to manage stormwater in sustainable manner. WSUD refers to measures or structural controls that are used for a given set of conditions to manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner. Pervious pavements address principles and goals set out in Water Sensitive Urban Design (WSUD technical manual 2003).

A pervious pavement is a structure that allows water to permeate through its structure while bearing loads. It overlies a reservoir storage layer. The water holding capacity of the sub base is of vital importance to reduce peak runoff. The main difference between a pervious and a conventional pavement is the permeability of the surface and the water holding capacity of the sub-base. Pervious pavements can reduce the flood peak and the volume of surface runoff as well as improve the quality of stormwater at source before it is transported to receiving waters. The water infiltrates through the pavement to a sub-base reservoir, from where it infiltrates slowly to the sub-grade soil and/or harvested for fit for purpose use or drains slowly to receiving waters.

A number of researchers (Borgwardt 1994; Pratt et al. 1995; Suarman et al. 1999; Valkman 1999) have discussed the potential of clogging in pervious pavements due to trapping of sediments limiting the effective life span of the pavement. Urban Water Resources Centre at the University of Adelaide (2002) defined effective life of a pavement as the number of years in service, until the hydraulic performances has dropped to an unacceptable level. At this point, the pavement would be regarded as having failed and remedial works required. The paper reports results from case studies carried out to investigate clogging potential of pervious pavements followed by the results obtained from laboratory tests carried out to gather information on the degree of sediment retention, reductions in infiltration rates and stormwater quality improvements especially the behaviour over time. The experimental rig constructed by Zhang et al. (2006) was used to determine the effective life of the C&M Ecotrihex (www.cmbrick.com.au) pavement.

STORMWATER MANAGEMENT USING PERVIOUS PAVEMENTS IN AUSTRALIA
Recent major Australian receiving water quality management initiatives such as the Port Phillip Bay Study, Perth...
Coastal Water Study, South East Queensland Regional Water Quality Management Strategy and the Sydney Clean Waterways program have identified a need for greater attention to the way we deal with and manage urban stormwater quantity and quality at source (Wong 2006).

Urban cities such as Sydney and Melbourne carrying most of Australia’s population face significant challenges in the coming years maintaining reliable water supply. Therefore if possible every drop of water has to be used efficiently provided it is done an environmentally sustainable way. Stormwater had been considered as a nuisance for many years with the primary interest being to remove it from its source rapidly and direct it through a discharge mechanism to reach receiving waters. Acute water shortages and adverse impacts of pollutants on the environment and river health have forced a paradigm shift where stormwater is now seen as a valuable resource. This change in attitude is also reflected in the Victorian Government’s policy paper Our Water Our Future (2005). The Urban Stormwater: Best Practices Environmental Management Guidelines; Victorian Stormwater Committee (1999) requires authorities managing urban stormwater to achieve a 45% reduction in nitrogen load, 45% reduction in phosphorus load and an 80% reduction in suspended solids load. If designed appropriately and constructed, pervious pavements assist this through reducing and treating stormwater at source.

The use of pervious pavements is rapidly emerging as a popular urban stormwater management practice in Australia. However, there is limited published material to support efficient and effective design. Therefore design guidelines based on more laboratory and field tests are needed to convince practicing engineers, land developers, regulators and urban Councils and shires of the benefits of using pervious pavements. Based on literature, this initiative will initially increase the infiltration rate and improve the stormwater quality whilst with time, unless properly maintained, the pervious pavement will clog with entrapped sediments and loose its effectiveness.

Over the last decade a number of projects in Australia have successfully integrated this new construction concept. The Olympic Boulevard at the Homebush Olympic site in Sydney, constructed in 1999 is a major example. Furthermore, there are some roads that have been installed since 1998. Roads in Kiama and Smith Street, Manly Sydney are good examples. Another car park was constructed in July 1999 by City of Charles Sturt, using BORAL Formpave units at Kirkaldy Avenue, Adelaide. The car park located adjacent to the North Haven Football Clubrooms was constructed by the City of Port Adelaide Enfield in late 1999, using BORAL Formpave units. A Grasspave installation was done in 1997 on the premises of St. Elizabeth Anglican Church in Adelaide. There is also a pavement constructed in 1999 out of ROCLA Ecoloc pavement blocks at Fletcher Lane by the City of Charles Strut. However, long-term water quality and reductions in infiltration rate have not been monitored and tracked in anyone of these pavements and hence, the effectiveness of the design intent of the pavement in delivering its original objectives remains unknown.

### RESEARCH ON PERVIOUS PAVEMENTS

The surface infiltration rate depends on the pervious surface, bedding and sub-base materials. The pervious pavements could be separated into porous pavements and permeability pavements (Jayasuriya et al. 2005). Infiltration rates for porous concrete asphalt surfaces have been measured as high as 40,000–60,000 mm/h, but values are typically far lower and change with time as debris accumulates in pores in the surface or in inlets (Pratt et al. 1995).

Borgwardt (1994) from the Institute for Planning Green Spaces and Landscape Architecture has conducted a research on UNI ECO-STONE permeable paving. It was stated that high permeability is guaranteed when the pavers are constructed with 2–5 mm gravel chips in the drainage openings. The permeability was $10^{-2}$ m/sec ‘as laid’ however this number decreased over time. After 5 years, permeability was $10^{-3}$ m/sec. Borgwardt (1994) study clearly showed that the permeability of the pavement reduced with usage.

Abbott et al. (2000) reported results from tests conducted at a new car park, surfaced with small element concrete blocks. The infiltrations through the block surface itself and through the gaps between blocks were 550 mm/h and 27,000 mm/h respectively. At a similar car park, but after some years of use, it was noted that the presence of
dirt and oil spillage on the pavement significantly reduced the infiltration rates from both the blocks and the gaps between them. The surface infiltration rate of the porous blocks was assessed, both through the blocks themselves and via the gaps between blocks. There was a large variation in the block infiltration rate (250 mm/hr to 14,000 mm/hr), which was also the case with the tests on the gaps, but here the infiltration rates were 50 times higher (11,000 mm/hr to 229,000 mm/hr). The infiltration tests when repeated after a 10 month interval revealed that the blocks (in some cases) had become largely impermeable due to clogging, although the gaps between blocks still performed well.

The same permeable concrete blocks as used at Nottingham (Pratt et al. 1989) were used at Shire Hall in England for the surfacing of infiltration trenches along one side of a 6,500 m² block-paved car park. The car park, constructed in 1986, was graded to fall to one side, where a one meter wide infiltration surface intercepted the runoff. At installation, the infiltration rate of the concrete block surface, which contained a regular pattern of 50 mm diameter, gravel-filled holes for inflow was 4,500 mm/h. After six years use, the infiltration rate of the surface was 2,600 mm/h, which was still sufficient to ensure full interception of runoff, equivalent to a rainfall intensity over the whole car park at 60 mm/h (Pratt et al. 1989).

Australian researchers, Suarman et al. (1999) carried out a laboratory study on four potential permeable substrates or permeable surfaces conducted over a period of 24 simulated years. The simulation study used a sediment concentration inflow (80 mg/L), comparable to those which could be expected in the substrates beneath permeable car parks in stable and fully established Adelaide suburbs. Failure of the construction was said to be when hydraulic conductivity of the primary filter systems (upper 50 mm of substructure) falls to 1/3 of the ‘as constructed’ value. To achieve this condition 25 years (or longer) of sediment input was required for the four beds tested.

Valkman (1999) performed a laboratory study on the substructure of permeable pavings. 30 years of sediment loading was simulated via accelerated loading techniques. A sediment load of 200 mg/L was applied. Four different substrates were tested, two substrates for “Grasspave” and two substrates for “Formpave” (type of concrete block pavement). It was found that after simulating 5 years of sediment loading, the hydraulic conductivity dropped to 10% of its initial value. The hydraulic conductivity decreased until it reached equilibrium after 20 years in 3 laboratory pavements. The hydraulic conductivity determined 20 years after construction was approximately 2% of its “as constructed” conductivity value. For the substructure with 5 mm and 20 mm crushed rock, the reduction in conductivity reached equilibrium after 40 years at approximately 8% of its “as constructed” conductivity value.

The Urban Water Resources Centre (2002), at the University of South Australia has tested a laboratory model which consists of four test beds (Two test beds from BORAL Formpave, ROCLA Ecoloc and Grasspave). Two test beds containing BORAL Formpave blocks were installed in the rig, one of which was subjected to daily (equivalent to yearly) surface cleaning with stiff brush and vacuum to simulate a field street sweeping device. The second test bed was not cleaned. The results revealed that the hydraulic conductivity through the BORAL Formpave test beds was predictably high at the commencement of the test. Hydraulic conductivity declined throughout the 35 years from $4.8 \times 10^{-2} \text{ m/s}$ to $1.9 \times 10^{-2} \text{ m/s}$ (average of both test beds), an average reduction of 59%. Hydraulic conductivity of the ROCLA Ecoloc was similar to the BORAL Formpave test beds, though slightly lower throughout. Grasspave exhibited a hydraulic conductivity an order of magnitude lower again than the other three pavements under test. This was due to the propagating sand content in the base material and within the Grasspave mat. Sediment input equivalent to 35 years was simulated and sprayed over permeable surfaces over a period of 420 months. Over the 35 year simulation test ROCLA Ecoloc and Grasspave experienced declines in hydraulic conductivity of 68% and 75% respectively.

Based on the literature sighted the infiltration rate or hydraulic conductivity has reduced with time due to clogging in different types of pervious surfaces. In some of the reported studies the infiltration and the hydraulic conductivity reduced considerably (as high as 75%–90%). Furthermore, in the results reported by Borgwardt (1994) the permeability dropped by 90% within 5 years. Valkman (1999) has observed that the hydraulic conductivity varied with the size of the sub-base aggregates.
RESEARCH PROGRAM METHODOLOGY

Experimental setup

The design and construction of the experimental rig used in this study at RMIT University (Figure 1) was reported in Zhang et al. (2006). The permeable pavement was constructed in a 1.5 m × 1.5 m steel box with holes in the bottom plate for water to pass through. A rainfall simulator with 25 evenly spaced spray nozzles was set up above the pavement surface to cover an area of 1 m × 1 m. A picture of the pavement rig and the rainfall simulator is reproduced (Figure 1) from Zhang et al. (2006). Rainfall intensities applied can be controlled by a flow meter. The pavement has been designed in such a way that water flowing through the pavement could be collected from underneath the pavement via a funnel connected to the 1 m × 1 m area. The thickness of the bedding and the base layers of the pavement (Figure 2) were designed according to Shackel et al. (1996) recommendations.

Zhang et al. (2006) used the experimental pavement rig (Figure 1) to study the infiltration properties of the permeable pavement. In the current study the laboratory rig used by Zhang et al. (2006) was used to investigate the stormwater quality improvement when infiltrating through the pervious pavement. Sharpley et al. (1981), Usitalo et al. (2000) and Hsieh & Davis (2005) have prepared synthetic stormwater samples in the laboratory to carry out experiments to investigate the improvements to water quality parameters. For the present study the stormwater quality sample was prepared according to the recommendations of Hsieh & Davis (2005). The typical Australian stormwater quality values reported by Newton (2001) were used when preparing the synthetic stormwater quality samples. The required weights of pollutants were calculated and weighed by selecting appropriate sources of pollutants as shown in Table 1. As mentioned earlier the objective of the laboratory study was to investigate the improvements to stormwater quality parameters in the source water over time due to retention of sediments within the pavement.

The synthetic stormwater sample was sprayed uniformly over the surface of the laboratory pavement rig and rainfall was simulated over the permeable pavement. In the current study, a constant rainfall intensity of 90 mm/hr (2.25 × 10⁻² mm/s) was simulated for 1.5 hours. Zhang et al. (2006) reported Ks (saturated hydraulic conductivity) of the bedding material to be 4.45 × 10⁻² (mm/s). As rainfall intensity is less than the saturated hydraulic conductivity, the infiltration rate was considered to be equal to the simulated rainfall intensity. The pavement was contaminated with stormwater equivalent to 1 year of sediment load for each of the first three simulated events and two years of sediment load to each of the rest of the

Table 1 | Constituents of the synthetic urban stormwater sample

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration (mg/L)</th>
<th>Source of pollutant</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>141</td>
<td>Local soil sieved through 0.5 mm</td>
</tr>
<tr>
<td>TP</td>
<td>0.24</td>
<td>Na₂HPO₄</td>
</tr>
<tr>
<td>TN</td>
<td>2.63</td>
<td>NaNO₃, NH₄Cl</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>0.1</td>
<td>PbCl₂</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>0.06</td>
<td>CuCl₂</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>0.63</td>
<td>ZnCl₂</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.007</td>
<td>CdCl₂</td>
</tr>
<tr>
<td>Oil and greases</td>
<td>20</td>
<td>Used oil from a motor vehicle repair garage</td>
</tr>
</tbody>
</table>
simulations. Altogether, sediment loads or concentrations equivalent to 17 years were sprayed on to the pavement.

The infiltrated water was collected from a funnel installed at the bottom of the pavement rig and tested for pollutant concentrations. Considering the literature and the field of interest, Total Nitrogen (TN), Total Phosphorous (TP), Total Suspended Solids (TSS), heavy metals such as Lead (Pb), Copper (Cu), Zinc (Zn), Cadmium (Cd) and oil were selected as the most relevant and important pollutants to study in the current research. The time taken to collect every 0.5 L of water was recorded from the start of the simulation until there was no flow. For water quality analysis, the first three samples were taken at 15 minute intervals and thereafter samples were taken every 30 minutes to obtain the pollutograph.

RESULTS AND DISCUSSION

The data collected were analysed for both water quantity and water quality parameters. Figure 3 depicts the cumulative outflow versus time for different simulations. Figure 4 details the final output flow rates for each simulation run.

Based on Figure 3, the cumulative outflow volume collected within 150 minutes is equal to 109 L after 5 years of equivalent pollutants on to the surface. However, in the simulation run spreading 17 years of sediment on to the test rig, the collected cumulative outflow within 150 minutes reduced to 98 L. This clearly indicates that the clogging of pores due to sediment entrapping had reduced the hydraulic conductivity of the pavement structure by 10%.

According to Figure 4 the initial and the final out flow rates after 17 years of simulation are 1.26 L/min and 1.16 L/min respectively. The total percentage reduction in infiltration rate due to accumulation of sediments on the rig was 8%.

Pollutant removal efficiencies were calculated using event mean concentration (EMC) and the total volume of infiltrated water collected from each event. Pollutographs were drawn for each and every pollutant for every storm and event mean concentrations (Equation 1) were calculated. Figure 5 shows the pollutograph drawn for the 4th simulation which was equivalent to the accumulation of five years stormwater pollutants. The total water pollutant load per each rainfall event was calculated by multiplying the EMC by total infiltrated water volume collected underneath the test rig (Equation 2). The ratio between total pollutant loads added to the total pollutant load removed gave the pollutant removal efficiency (Equation 3).

\[
EMC = \frac{\sum_{t=0}^{T} Q_t C_t}{\sum_{t=0}^{T} Q_t}
\]

(1)

where

- EMC = Event mean concentration of a particular water quality parameters (mg/L)
- \(Q_t\) = Discharge at a given time (L/s)
\( C_t = \) Concentration of the water quality parameter at time \( t \) (mg/L)

\( T = \) Time base of the hydrographs

Total pollutant load = EMC 
\[ \times (\text{Total infiltrated volume of water}) \]  
(2)

Removal efficiency = \[ \frac{(\sum \text{Input load} - \sum \text{Output load})}{(\sum \text{Input load})} \]  
(3)

Table 2 gives the water quality parameters and the removal efficiencies of the C&M Ecotrihex surface for the simulated storm events. The removal efficiency of TSS and Cu is almost the same for all simulated storm events and is around 95% for both pollutants. The reason behind this result is the porosity of the pavement and its capability to filter most of the TSS. The removal efficiency of oil is between 85% to 97%. The results obtained for Zn shows that the removal efficiencies are very low and in some events there was a slight gain in Zn. This could be due to the decay of the steel box that was used to set up the experimental rig. The TP and TN removal efficiencies reduced from 63% to 12% and 53% to 22% respectively over the 17 year of simulation. This could be due to leaching of TN and TP in the granular material used in the sub-base and the decomposition of aggregates used for the pavement structure. The removal efficiencies of Cd and Pb were below detectable levels.

MAINTENANCE OF PERVERUS PAVEMENTS

A number of researchers (Pratt 1997; Kobayashi 1999; Rushton 2002; Dierkes et al. 2002) reported that maintenance of pervious pavement plays an important role in ensuring its on-going performance. Maintenance of pervious pavements depends on the pavement type and the environment in which it is constructed. Proper maintenance is essential to ensure its efficient operations. However, the maintenance required is similar to what is currently applied to a traditional pavement. The main difference is that a pervious pavement should be vacuumed rather than swept. Vacuuming removes sediment and debris which block the infiltration of runoff. Frequency of vacuuming depends on the amount of sediment carried by wind, vehicles or pedestrians etc. into the pervious pavement from neighbouring areas.

The EPA (1999) recommended sweeping the pavement at least four times a year and hosing the top layer with high pressure water to remove pavement clogging.

It is important to maintain the pervious pavement surface with regular cleaning program to retain the high infiltration rate. It is also important to minimise the pollutant coming from the surrounding area on to the surface. This could be achieved by integrating other WSUD features before the pervious pavement. For example the

<table>
<thead>
<tr>
<th>Simulated number of years</th>
<th>Total pollutant removal efficiency (%)</th>
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<tbody>
<tr>
<td></td>
<td>TN</td>
</tr>
<tr>
<td>1</td>
<td>62.94</td>
</tr>
<tr>
<td>2</td>
<td>59.95</td>
</tr>
<tr>
<td>3</td>
<td>58.34</td>
</tr>
<tr>
<td>5</td>
<td>46.03</td>
</tr>
<tr>
<td>7</td>
<td>28.62</td>
</tr>
<tr>
<td>9</td>
<td>22.74</td>
</tr>
<tr>
<td>11</td>
<td>17.53</td>
</tr>
<tr>
<td>13</td>
<td>11.45</td>
</tr>
<tr>
<td>15</td>
<td>10.52</td>
</tr>
<tr>
<td>17</td>
<td>12.02</td>
</tr>
</tbody>
</table>
construction of a grass swale around the pervious pavement car park before stormwater is washed off on to the pervious surface would greatly assist the longevity of the pavement by entrapping sediment.

**CONCLUSION**

The pollutant trapping efficiency of C&M Ecotrihex permeable pavements was examined under laboratory conditions by simulating storms over the experimental rig for a period of 17 years. The laboratory results clearly show that the removal efficiencies of TSS, oil and Cu reduced from approximately 98% to 80% after spraying loads equivalent to 17 years of pollutants on the pavement rig. Total Nitrogen and Total Phosphorous removal efficiencies dropped significantly after about 6 years into the 17 year simulation period. The initial infiltration rate reduced by 8% after 17 years due to entrapping of sediments. Therefore clogging is not considered a major concern, and pervious pavements can therefore be used for more than 20 years without total remediation.

The application of pervious pavements can result in long term environmental benefits such as reduction in runoff volumes and improvements in water quality parameters entering receiving waters. However, an appropriate maintenance program must be planned before the construction of the pervious pavement. Regular maintenance such as vacuuming or the use of high pressure water jets will help to reduce the clogging of the pavement.

The results obtained clearly show that pervious pavements effectively reduce the volume of water and peak discharge and reduce the pressure on urban drainage infrastructure. Furthermore, pervious pavements are capable of removing pollutants that are present in urban stormwater. These preliminary results from the laboratory pavement rig are currently being used in the design of a field scale experiment planned for a commercial car park in Melbourne.

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