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## Are Infiltration Capacities of Clogged Permeable Pavements Still Acceptable?

Les capacités d'infiltration de revêtement poreux "colmatés" restent-elles acceptables ?

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### RÉSUMÉ

Cette étude décrit des études de terrain sur la capacité d'infiltration de 18 systèmes de chaussée perméables installés aux Pays-Bas et en Australie. L'âge des chaussées varie de 1 à 12 ans. En utilisant le test d'infiltrométrie, les performances des chaussées ont été comparées en fonction de leur capacité d'infiltrer une pluie de trois mois dans le cas des revêtements australiens, et une capacité d'infiltration européenne de 97,2 mm/h pour les revêtements néerlandais, en supposant un rapport imperméable/perméable de 4 à 1 pour le bassin versant. La plupart des chaussées testées suivent globalement une courbe hypothétique décroissante du taux d'infiltration avec l'âge de la chaussée. Toutefois, celles-ci sont réparties en deux groupes distincts (néerlandais et australiens) avec les chaussées anciennes australiennes qui semblent maintenir des taux d'infiltration élevés par rapport à leur âge.

### ABSTRACT

This study describes field investigations of the infiltration capacity of 18 permeable pavement systems installed in the Netherlands and in Australia. The ages of the pavements varied from 1 to 12 years. Using infiltrometer testing, the performance of the pavements have been compared in terms of their ability to infiltrate; a three month ARI storm event in the case of the Australian pavements; or the minimum European infiltration capacity of 97.2 mm/h for the Dutch pavements, assuming a 4:1 impermeable to permeable ratio for the catchment area. Many of the tested pavements broadly follow a hypothetical decay curve of infiltration rate with age of pavement. However, these are clustered into two distinct groups (Dutch and Australian) with the older Australian pavements appearing to maintain higher infiltration rates relative to their age.

### KEYWORDS

Clogging, Infiltration, Permeable pavement, Water sensitive urban design,

## 1 INTRODUCTION

Pavements are an everyday part of the urban landscape that can have a significant environmental impact. Typically two-thirds of all the rain that falls on potentially impervious surfaces in urban catchments is falling on pavements (Ferguson, 2005) and pavements are responsible for the generation of excess runoff which is often contaminated with heavy metals and hydrocarbons (Fletcher et al., 2005; Hatt et al., 2009). They also inhibit groundwater recharge and this can result in local water shortages. Pavements are very much at the forefront of the planning process for developers and local authorities who have to address stormwater flooding and water quality issues. This is because impervious surfaces such as pavements have a major impact on downstream flooding, receiving water quality and on the health of natural ecosystems.

Conventional pavements designed for use by vehicular traffic typically consist of a sub-grade, one or more overlying basecourses of compacted pavement material and a surface seal. An integral aspect of conventional pavement design involves preventing the entry of water into the pavement, via the seal or the paving joints, to protect the integrity of the underlying basecourse and sub-grade (Beecham et al., 2009).

Permeable pavements are a relatively new technology and have quite different objectives and design requirements to conventional pavements and can be used as an alternative to conventional impervious hard surfaces, such as roads, car parks, footpaths and pedestrian areas (Beecham et al., 2010). Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and basecourses where it is filtered through the various layers. This results in many stormwater management and environmental benefits. The filtered stormwater is then either harvested for later reuse or released slowly into the underlying soil or stormwater drainage system (Fletcher et al., 2005).

Even for systems not specifically designed for harvesting and reuse, the storage capacity in the basecourse layers can be utilised to intercept significant rainfall events. Permeable pavements can significantly reduce runoff volumes and discharge rates from paved surfaces (Pratt et al., 1995; Hunt et al., 2002; Fletcher et al., 2005; Bean et al., 2007; Collins et al., 2008). These reductions can potentially minimise the risk of downstream flooding. Permeable pavements also provide considerable water quality improvements by treating and trapping stormwater pollutants (Pratt et al., 1989; Dierkes et al., 2002; Brattebo and Booth, 2003; Siriwardene et al. 2007).

Over the last decade or so, there has been a steady increase in the number of permeable pavement systems installed worldwide. This has generally been in response to various stormwater management initiatives, such as water sensitive urban design (WSUD) in Australia, sustainable urban drainage systems (SUDS) in Europe and low impact development (LID) in the USA and Japan, to reduce stormwater pollution and downstream flows (Beecham et al., 2012).

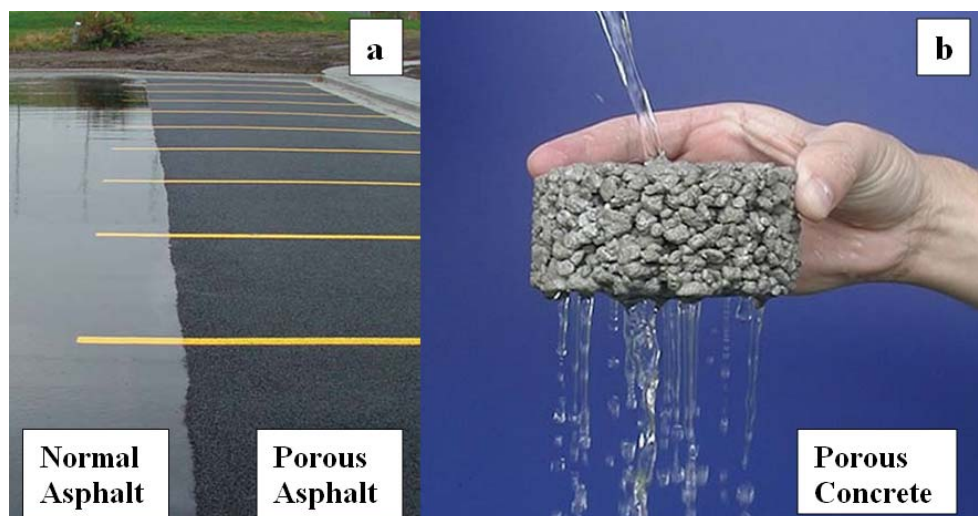


Figure 1 - a) Normal and Porous Asphalt (NAPA, 2012); b) Porous Concrete (Hall, 2012)

Permeable (or porous) pavements come in several forms, and are either monolithic or modular (Fletcher et al., 2005). Monolithic structures include porous asphalt and porous concrete (Figure 1), that allow infiltration through the pavement surface only. Porous asphalt is similar to typical hot mix

asphalt but the fine portion of the aggregate is omitted. Likewise, most of the fine aggregates included in the production of traditional concrete are omitted during the production of porous concrete. Modular structures include (impermeable) concrete block pavers with open joints or apertures (Figure 2) to allow infiltration through the joints, and porous concrete block pavers that allow infiltration through both the paver surface and the paving joints. Concrete paving blocks are generally referred to as permeable interlocking concrete pavers (PICPs).

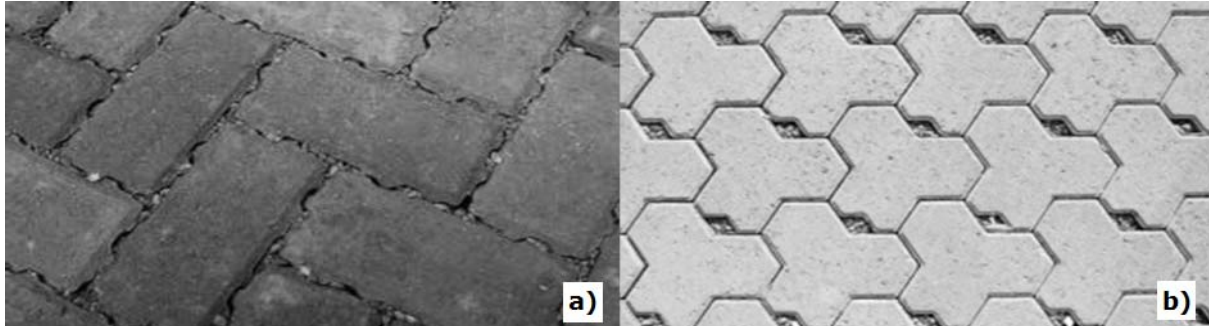


Figure 2 - PICPs with Wide Joints (a) and Apertures (b)

PICPs are generally designed so that there is a significant open space between the pavers to allow water to infiltrate into the pavement structure. This is either achieved by way of specially designed paving shapes that include small apertures in the paving surface (Figure 2b) or with slots or spacing lugs that are cast into the perimeter of the pavers to keep them apart (Figure 2a). The joints or spaces between PICPs are not filled with sand or other binders as they are with conventional pavers. Instead, the open spaces between the pavers are usually filled with the same 2 to 5 mm aggregate that is used for the paving bedding layer. Filling the joints with bedding aggregate promotes rapid infiltration between the pavers. A typical PICP paving bed cross section is shown in Figure 3.

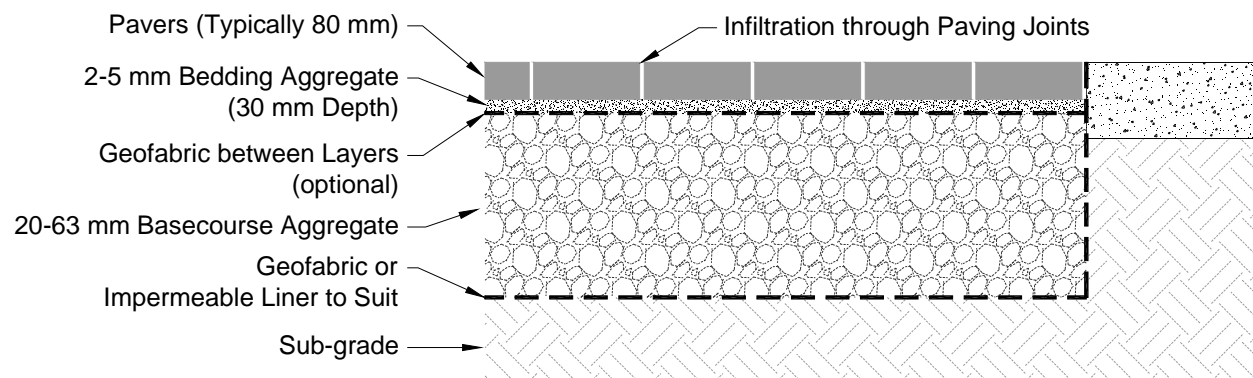


Figure 3 - Typical Permeable Pavement Structure

In an experimental investigation, Lucke and Beecham (2011) found that only 8.3% of the total sediment mass trapped in a permeable pavement system was retained in the upper geofabric layer. Over 90% of the sediments were trapped in the paving and bedding aggregate layers of the test pavements. This is further evidence that the beneficial role of geofabric in filtering out sediments and protecting the integrity of the underlying basecourse may not be significant enough to warrant its inclusion in the permeable pavement installation. This finding may be particularly important to geotechnical engineers because of the layering effects and the potential slip plane that inclusion of a geofabric liner could create within a permeable pavement system. Consequently the upper geofabric layer is often omitted in modern designs.

Infiltration rates of newly installed permeable pavement systems have been shown to be extremely high. However, as Yong and Deletic (2012) point out, it is the long-term infiltration performance of a pavement that determines their ultimate success or failure. To date, the number of research studies undertaken on permeable pavements that have been in operation for several years has been limited (Borgwardt, 2006; Pezzaniti et al., 2009; Lucke and Beecham, 2011).

Several research studies have demonstrated that urban stormwater runoff contains significant concentrations of suspended sediments and a variety of pollutants including heavy metals, total phosphorous (TP), total nitrogen (TN), oils and other hydrocarbons (Sartor et al., 1974; Sansalone,



1998; Duncan, 1999; Dierkes et al., 2002, Boogaard et al., 2010). There is therefore some industry concern that permeable pavements used as source control devices, and designed to infiltrate runoff, will tend to clog quickly and result in a significant loss of infiltration capacity. These concerns have led to further research into the clogging processes that take place in permeable pavements (Pratt et al., 1995; Brattebo and Booth, 2003; Pezzaniti et al., 2009; Lucke and Beecham, 2011).

Clogging in pervious pavements is inevitable and further research is required before any reliable predictions can be made on the practical lifespan of these systems (Yong and Deletic, 2012). However, a number of research studies have shown that the even visually "clogged" systems can still produce significant infiltration rates through the pavement surface. This raises the question of whether infiltration capacities of clogged permeable pavements are still acceptable.

In Australia, WSUD treatment devices are generally installed to enhance water quality and to attenuate and minimise peak flowrates from urban catchments. They are not usually expected to treat the runoff from large storm events and are typically only designed to cope with the runoff from small storms, for example often only up to the 3 month Average Recurrence Interval (ARI) design storm intensity (Lloyd et al., 2002; Melbourne Water, 2012; ACTPLA, 2007).

This paper reviews infiltration performance studies undertaken on 18 permeable pavements systems in Australia and the Netherlands. The infiltration rates of a number of permeable pavements systems that have been in service for between 1 and 12 years were measured. The broad aim of this study was to quantify the reduction in infiltration capacities over time in order to ascertain whether the performance of the clogged permeable pavement systems was still acceptable.

## 2 METHODS

A number of studies have used surface infiltration testing to quantify the hydrologic performance of permeable pavement systems. This is generally undertaken by measuring the infiltration rate of water through a particular section of the pavement surface. While a variety of infiltration test procedures have been used, most are based on some type of modified single or double-ring infiltrometer test. Ring infiltrometers are normally used for measuring the infiltration rate of soils. The main problem with using the infiltrometer test is that the test rings are not able to penetrate the concrete test surface to seal against leakage, as they are in soil infiltration tests (Bean et al. 2007). Therefore, the rings need to be sealed against the pavement surface using some type of waterproof sealant (Figure 4) or adhesive. This procedure is outlined in Australian Standard AS 4693.5 (2004).

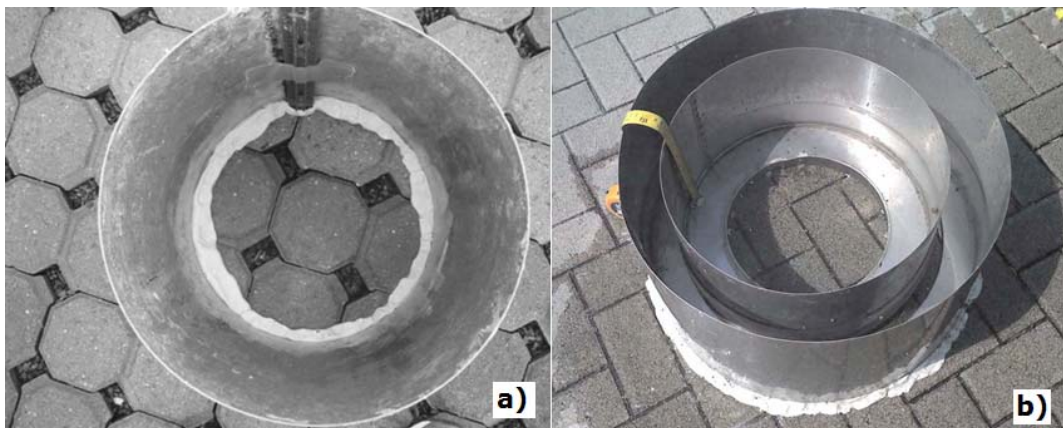


Figure 4 – Modified Ring Infiltrimeters for Permeable Pavement Testing with Waterproof Sealant  
(a) Single Ring (Bean et al., 2007) (b) Double Ring (Fassman et al., 2010)

The single ring infiltrometer test is generally used for pavements with an infiltration rate that is too high to maintain a hydraulic head. This variation of the falling head method is also known as the surface inundation test (Bean et al., 2004). It works by sealing the ring to the pavement and inundating it with water from a bucket and measuring the head loss over time. This test is less accurate than the double ring infiltrometer test but it can still produce a reasonable estimate of the surface infiltration rate (Bean et al., 2004).

A further variation on the ring infiltration test was introduced by Gerrits and James (2002). In order to test a larger area of pavement, they fabricated a square shaped single ring infiltrometer (Figure 5a). The area of the square ring was approximately  $0.5\text{m}^2$  and this allowed them to test the infiltration rates through 36 paving joints and apertures simultaneously. Beecham et al. (2009) expanded on this

variation and constructed a square double ring infiltrometer for their study (Figure 5b) that could be used to test a 1 m<sup>2</sup> area of the paving surface.

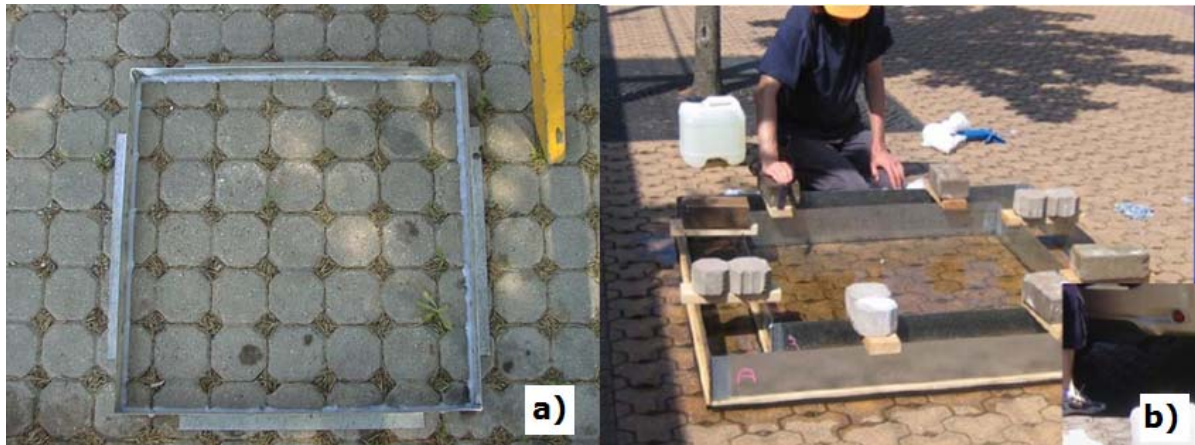


Figure 5 – a) Square Shaped Single Ring Infiltrometer (Gerrits and Smith, 2002),  
b) Square Shaped Double Ring Infiltrometer (Beecham et al., 2009)

Dierkes et al. (2002; 2005) and Borgwardt (2006) attempted to create more realistic infiltration conditions by combining the single ring infiltrometer test with an overhead rainfall simulator (Figure 6). The rain simulation test they developed used an apparatus called a drip infiltrometer to distribute 'rain' onto the pavement surface. In this test, a steel ring was cemented to the pavement surface and the rainfall intensity (flow rate) of the drip infiltrometer was adjusted to maintain a level between 1 and 3 mm within the ring so that no unrealistically high water pressure head is created, as is the case with other infiltration tests (Dierkes et al., 2005). The results demonstrated that this test was effective in simulating actual rainfall events. However, the major limitation of this type of test is in the cost, complexity and amount of test equipment required.



Each of the testing methods outlined above were considered for use in this study. While the rain simulation test used by Dierkes et al. (2002; 2005) and Borgwardt (2006) was considered the most accurate method, the time, cost and complexity involved with the construction and use of the model deemed it impractical for this project. It was therefore decided that the square shaped double ring infiltrometer developed by Beecham et al. (2009) would be used in this study for the Australian testing. The double ring infiltrometer method used by Fassman et al. (2010) was used for the Dutch testing. For pavement sections where the infiltration rate was too high for this method to function correctly, a surface inundation test was used.

Surface infiltration testing using double ring infiltrometers was undertaken on 18 different PICP installations in Australia and the Netherlands. The pavement installations tested had a variety of functions including pedestrian areas, car parks, roads and residential streets. The PICPs had been in service for a period of between 0 and 12 years before testing was undertaken. Six of the 18 pavements tested were in New South Wales (NSW), Australia and three of the pavements were located in Adelaide, South Australia (SA). The remaining nine PICP installations tested were located at various sites throughout the Netherlands. The PICP testing sites are shown in Table 1.

Figure 6 - Test Rig for Rain Simulation Testing (Dierkes et al., 2002)

Table 1 – PICP Test Locations

Location	Site	Age at Testing (years)	$I_{1y,5min}$ (mm/h)	$I_{3m,5min}$ (mm/h)
New South Wales	Sydney Cricket Ground	11.0	106	53.0
	Victoria Park	10.0	103	51.5
	Manly - Smith St	8.0	96.5	48.3
	Botanic Park Estate	9.0	99.9	50.0
	Olympic Park	11.0	89.2	44.6
	Kiama	12.0	113	56.5
South Australia	Kirkcaldy Av	2.1	40.8	20.4
	Fletcher Lane	2.1	39.5	19.8
	UniSA Carpark	8.0	40.0	20.0
Location	Site	Age at Testing (years)	Minimum Infiltration rate (mm/h)	
Netherlands	Urk (1)	3.75	97.2	
	Urk (2)	1.5	97.2	
	Edam	2.75	97.2	
	Scherpenzeel	3.5	97.2	
	Heiloo	2.5	97.2	
	Rotterdam	1	97.2	
	Werkendam	4	97.2	
	Schoonhoven (1)	1	97.2	
	Schoonhoven (2)	1	97.2	

Rainfall intensities in Australia are generally much greater than in Europe and many other parts of the world. The successful design of permeable pavement systems is highly dependent on the rainfall characteristics occurring at the proposed PICP location (Lucke and Beecham, 2011). WSUD design guidelines typically state that permeable pavements should be designed to manage runoff from small storms of up to the 3 month ARI design storm intensity (ACTPLA, 2007; GCCC, 2007). Therefore, for a permeable pavement to be deemed to be functioning properly, it must be able to infiltrate the volume of rainwater falling on the pavement during a 3 month ARI design storm intensity event.

Intensity frequency duration (IFD) data in Australia is typically only available in durations of 1, 2, 5, 10, 20, 50 and 100 years. A method for estimating the three monthly ARI values is therefore required. Various guidelines on estimating low flows can be found in the literature. However, for this study, it was decided to use the method recommended by the Gold Coast City Council in Australia (GCCC, 2007). They recommend applying a 50% reduction factor to the one year, 5 minute duration IFD value ( $I_{1y,5min}$ ) at the location in question to estimate the 3 monthly ( $I_{3m,5min}$ ) IFD value. This method was used to calculate the 3 monthly ARI values shown in Table 1. The  $I_{1y,5min}$  IFD values for the Australian sites were obtained from the Australian Bureau of Meteorology website (BOM, 2012).

Newly installed permeable pavements in Germany and many other parts of Europe, including the Netherlands, must demonstrate a minimum infiltration capacity of 270 l/s/ha, or 97.2 mm/h (FGSV, 1998; OCW, 2008; Wohlfahrt, 2012). Even though this infiltration rate has been shown to be excessive (Dierkes et al., 2002), many designers apply a blocking factor of 50% to this rate to allow for deterioration in infiltration performance over time. For example, the Netherlands is currently developing a standard for the construction of permeable pavements which advises designers to apply a clogging factor of 2.0 to the general European standard resulting in a minimum average infiltration capacity of 540 l/s/ha, or 194mm/h (KIWA, 2012). However, in this study, we have used the recommended minimum European infiltration rate of 97.2 mm/h for the Dutch sites shown in Table 1.

The average infiltration capacities of the 18 PICP installations listed in Table 1 were tested in this study to determine whether they can still infiltrate the 3 month ARI design storm event after a number of years in service. The average infiltration capacity of the pavements were compared with the design infiltration capacity using the following equation:

$$\% \text{ of comparison intensity} = 100 \times (\text{average infiltration capacity, L/s/ha} \div \text{minimum design infiltration capacity, L/s/ha})$$

PICP pavements are often designed to treat the stormwater runoff from adjacent impervious areas, particularly in car park applications. This means that the infiltration capacity of the PICPs must be proportionately higher to manage the runoff volumes generated from the larger pavement surface area. Previous research by Dierkes et al. (2005) examined the performance of PICPs treating the runoff from contributing areas in various ratios of up to 16:1 (impermeable area : permeable area). Their research suggested that a maximum contributing area ratio of 4:1 is appropriate for PICPs. This means that the required surface infiltration capacity would need to be five times higher for a contributing area ratio of 4:1.

### 3 RESULTS AND DISCUSSION

Figure 7 shows the surface infiltration results expressed as a percentage of the comparison infiltration capacity required to cope with the design ( $I_{3m, 5min}$  or 97.2 mm/h, respectively) runoff from a pervious/impervious contributing area ratio of 4:1. One Adelaide pavement is not shown on this graph as it had an extremely high comparison infiltration rate (1000%) and was treated as an outlier. Overall, eight of the 18 sites are above 100% meaning that less than half of the sites were still performing satisfactorily with infiltration rates exceeding those required to satisfy either a three month ARI storm event for the Australian pavements, or to satisfy the minimum European infiltration rate of 270 l/s/ha (97.2 mm/h) performance criteria.

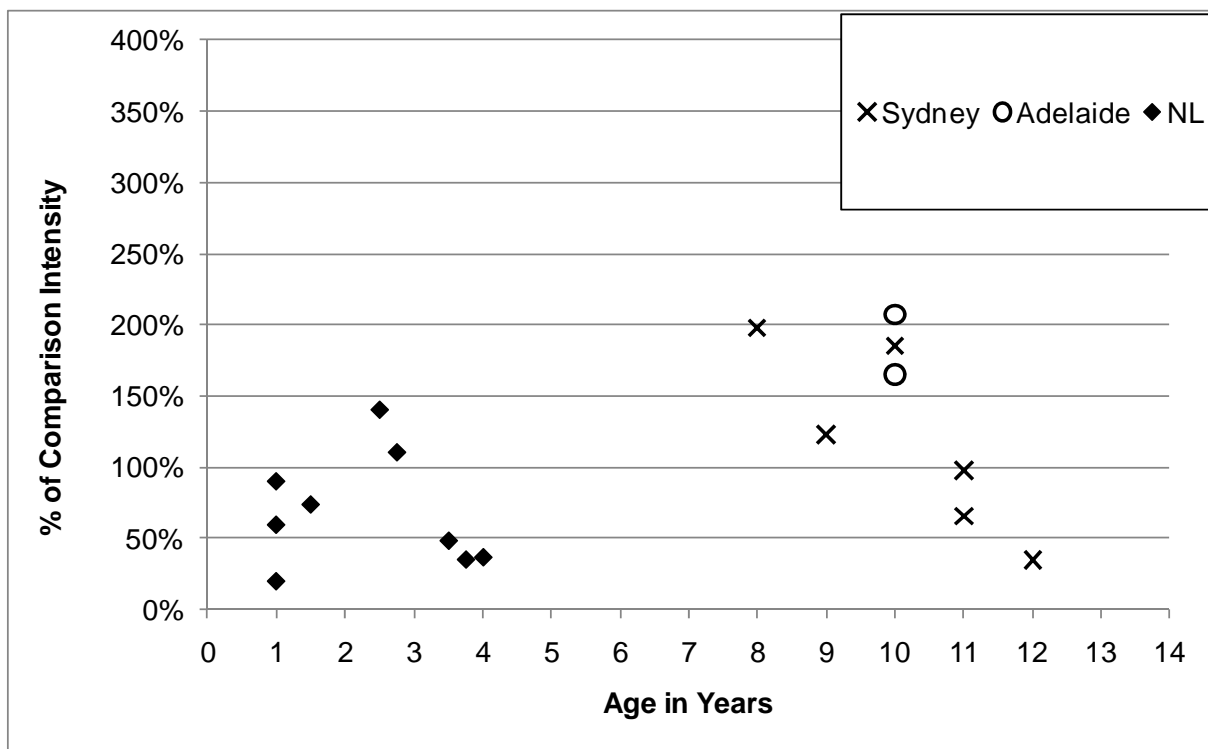


Figure 7 – PICP Surface Infiltration Results as a Percentage of Respective Australian and Dutch Comparison Intensity Required for a 4:1 Contributing Area Ratio

Borgwardt (2006) believed that infiltration performance is highly affected by the age of the pavement because of the entrainment of mineral and organic fines in the upper 20 mm of joint fillings or the pores of porous paving blocks. He postulated that there is a decrease to between 10 and 25% of a pavement's "as constructed" infiltration rate within 12 years of service. Interestingly, Figure 7 does show a general decrease in infiltration rates with time for the Australian (Adelaide and Sydney) pavements. This is partially true for the Dutch pavements - one Dutch pavement had a very low infiltration capacity after only one year of service, and two pavements approximately 3 years old had an infiltration capacity higher than newer pavements. This may be because of the operating conditions of these pavements or superior maintenance procedures, which are being considered in future research.



The results are also clustered into two distinct groups with the older Australian pavements appearing to maintain higher infiltration rates than pavements in the Netherlands. There are a number of possible explanations for this including different spatial and temporal patterns of rainfall leading to different clogging rates in each country, different maintenance regimes and different operating conditions. No account was taken of the maintenance regimes for the pavements in this study. It is possible that some of the older, well-performing pavements may have retained a high infiltration capacity because of the standard of maintenance. Investigation of the effects of maintenance and operating conditions will be investigated in a future study.

## 4 CONCLUSION

This study has adopted a novel approach to assess the serviceability of permeable pavements. Using ring infiltrometer testing, nine permeable pavements in Australia and nine in the Netherlands have been compared in terms of their ability to infiltrate either a three month ARI storm event for the Australian pavements, or to satisfy the minimum European infiltration rate of 270 l/s/ha (97.2 mm/h), assuming a 4:1 impermeable to permeable ratio for the catchment area. Approximately half of the pavements tested were not able to infiltrate to these standards.

This study indicates that the infiltration capacity of permeable pavements generally decreases with pavement age, probably because of clogging. However, this relationship was not as clear in the Netherlands as it was in Australia. Furthermore, the permeable pavements in Australia exhibited a higher infiltration rate compared to those in the Netherlands, despite being several years older. The researchers plan to extend this study by including pavements from other countries. It is also intended to investigate the influence of the type of system, operating conditions and maintenance on the infiltration capacity of the pavements.

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