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Review

A Review of Permeable Pavement Clogging Investigations and Recommended Maintenance Regimes

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Abstract: Understanding clogging mechanisms in permeable pavements can help optimize the required maintenance regime. In this review paper, methods for investigating clogging mechanisms are described. These include surface infiltration methods, the use of embedded sensors, and the development of modelling tools. Previously conducted surface infiltration tests indicate the importance of the age of a permeable pavement system and also local climatic conditions, including rainfall intensity. The results indicate that porous concrete generally has the highest infiltration capacity and this is followed by permeable interlocking concrete pavement and then porous asphalt. The measured infiltration rates decreased significantly even within two years of installation. There was an indirect relationship between surface infiltration rates and the age of the pavements. It was also found that the rainfall characteristics are important in selecting the type of pavement. Sensor technologies have been used mainly in the United States and there has been a reluctance to use such technologies in other parts of the world. Few studies have been conducted into modelling the changing performance of permeable pavement systems over time and there is a need to develop more general models. Various methods and machinery have been developed for cleaning and maintaining permeable pavements and there is no universally preferred approach currently available. Indeed, several of the commonly used maintenance methods have been shown to be relatively ineffective.

Keywords: permeable pavement; porous concrete; porous asphalt; clogging; sensors; infiltration; maintenance

1. Introduction

Permeable pavement is one of the recommended technologies for both low impact development (LID) in the United States of America (USA) [1–3] and water sensitive urban design (WSUD) in Australia [4,5]. LID and WSUD both aim to minimise the effects of urbanization by attenuating runoff peak flows and providing water quality control in order to protect downstream waterbodies, largely through mimicking natural processes [6,7]. Permeable pavements systems are able to both mitigate urban runoff [8] and to improve stormwater quality [9–11]. In addition, if combined with an underground reservoir in warm climates such as Australia, it is then possible to reuse the harvested water in urban landscapes [10,12]. In addition, in areas with native soils of low infiltration capacity, the addition of underground reservoirs improves the exfiltration performance of the permeable pavement system [13,14]. There are three types of common permeable pavements, namely porous concrete (PC), permeable interlocking concrete pavers (PICP), and porous asphalt (PA) [15–17].

A profile of a typical permeable pavement section for the USA is shown in Figure 1. This profile includes a type of permeable pavement on top, an underlying bedding layer (in the USA this is made of American Association of State Highway and Transportation Officials (AASHTO) No. 8 aggregate), a base or choker layer (in the USA this is made of AASHTO No. 57 aggregate) and finally a subbase or storage gallery (in the USA this is made of AASHTO No. 2 stone).

Clogging of a permeable pavement system is an issue that reduces the functionality of this LID/WSUD technology. Several factors can potentially affect the start and progression of clogging of a permeable pavement system. These include rainfall characteristics, catchment soil characteristics, air quality and temperature, contributing drainage area, and traffic types and volumes [18]. Measuring the surface infiltration rate of a permeable pavement is an important method for monitoring the performance and functionality of this technology. A number of studies have adopted or developed methods to measure infiltration rates.

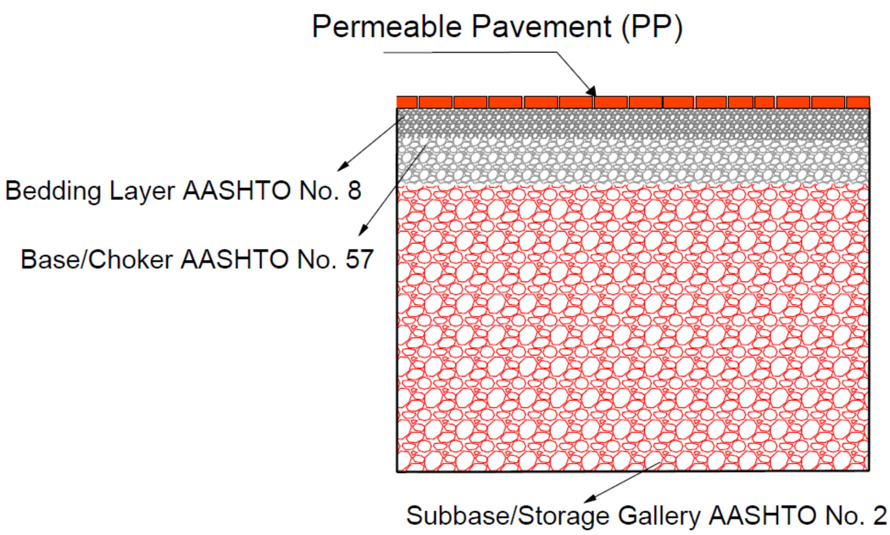


Figure 1. A typical profile of a permeable pavement system with underlying layers.

The objective of this study was to review the clogging mechanism and various types of permeable pavement surface infiltration rates with respect to age and maintenance regimes. Available sensor technologies and numerical models were also investigated.

2. Clogging Investigation

2.1. Infiltration Methods

Permeable pavements should be able to infiltrate stormwater runoff water into the basecourse layer and eventually exfiltrate it into the surrounding native soils. Measuring the surface infiltration rates of permeable pavements assesses this infiltration capability. Continuous monitoring of permeable pavement surface infiltration rates also indicates the requirement for ongoing maintenance in order to maintain infiltration capacity.

Surface infiltration tests measure how long it takes to infiltrate a known volume of water. Single-ring and double-ring infiltration methods have been used for soil infiltration tests and have been adopted for measuring the infiltration rates of permeable surface [19]. Vertical infiltration is of primary interest for permeable pavements and in double ring tests the reason for having the outer ring is to reduce the effects of horizontal infiltration. The American Society for Testing and Materials (ASTM) has recommended several methods for measuring infiltration rates in permeable pavement surfaces. ASTM C1701/C1701M—17a describes recommended methods for measuring the infiltration rate of pervious concrete (PC) [20], while ASTM C1781 describes recommended methods for measuring the infiltration rate of permeable interlocking concrete pavements (PICP) [21]. Because of the labour intensiveness of these tests, several researchers have tried to improve the methods and make it easier and more cost effective for end users [22,23].

A simple method for quick and simple infiltration tests has been developed [22]. This method was compared with ASTM C1701 and the results showed good agreement up to infiltration rates of 250 mm/h. Beyond this point, the new method underestimated the infiltration rate compared to the ASTM method. This could be because water moves laterally when the ASTM method used. A Cantabrian Fixed (CF) Infiltrometer was used in a study of porous asphalt clogging with void ratios of between 20% and 33% [24]. Multiple scenarios of clogging with various pavement slopes were tested in this study.

Two of the most common tests measuring infiltration rates through porous asphalt and pervious concrete include the National Center for Asphalt Technology (NCAT) permeameter and the ASTM C1701 method that was used for a study in California [25]. The infiltration values measured with the ASTM method were 50% to 90% (75% on average) smaller than those measured with the NCAT method. The agreement between these two methods improved when a larger permeameter cylinder diameter was used for the ASTM method.

The performance of two experimental test methods that were developed in the Netherlands to determine the surface infiltration rate of existing permeable pavement installations were trialled in Australia [23]. The two methods were the falling head and the constant head full-scale methods. Both of these methods required the submergence of a large area of the pavement to determine the surface infiltration rate. For comparing the results, multiple double ring infiltrometer tests were also conducted. The results demonstrated that the most accurate results were associated with the falling head full-scale testing method. Recently, a stormwater infiltration field test (SWIFT) method was developed in Australia [26] as a fast and inexpensive method for permeable pavement assessment. The SWIFT method was compared with the single-ring infiltrometer test (ASTM C1781M-14a) method and a good agreement was found between these methods.

2.2. Sensors and Modelling Efforts

Similar to the adoption of single and double ring infiltration for permeable pavement infiltration tests, other technologies have also shown promising results in terms of measuring surface clogging [27]. Both time domain reflectometers (TDRs) and water content reflectometers (WCRs) have been used for detecting soil moisture and for studying water infiltration and movement in soils. However, these types of sensors are not able to estimate the moisture level in the porous media of granular aggregates that are used under permeable pavements [27], but rather they are just able to give an indication of volumetric water content. By using these types of sensors with continuous recording, it is possible to study clogging generation and progression on a permeable pavement surface.

Various types of TDRs and WCRs have been used for clogging mechanism investigations in various locations across the USA [14,28,29]. These locations had either side road parking strips or permeable pavement parking lots. In these studies, the hypothesis was that the clogging progresses from the upstream boundary of the permeable pavement section toward the downstream boundary and this was generally supported by earlier studies [14,28]. In the case of permeable pavement strips, the clogging progressed from the road curbside perpendicular to the road car traffic. Tipping bucket rain gauges were buried under the permeable pavement section in one of these studies [14] as an alternative method for studying the clogging mechanisms. Cumulative recordings from the buried tipping bucket rain gauges were compared with data from a tipping bucket rain gauge that was located on a rooftop of a nearby building. The buried tipping bucket rain gauges were also able to track the clogging progression along the pavement section.

Pressure transducers have also been used in permeable pavement parking lots that were designed with underlying reservoirs or storage galleries. Pressure transducers are able to record the depth of water ponding inside the storage gallery [14,15,30]. It is then possible to calculate the capture rates and hydraulic head inside the storage gallery. Once the change in capture rate and the hydraulic gradient variations over time are known, it is possible to track the progression of clogging.

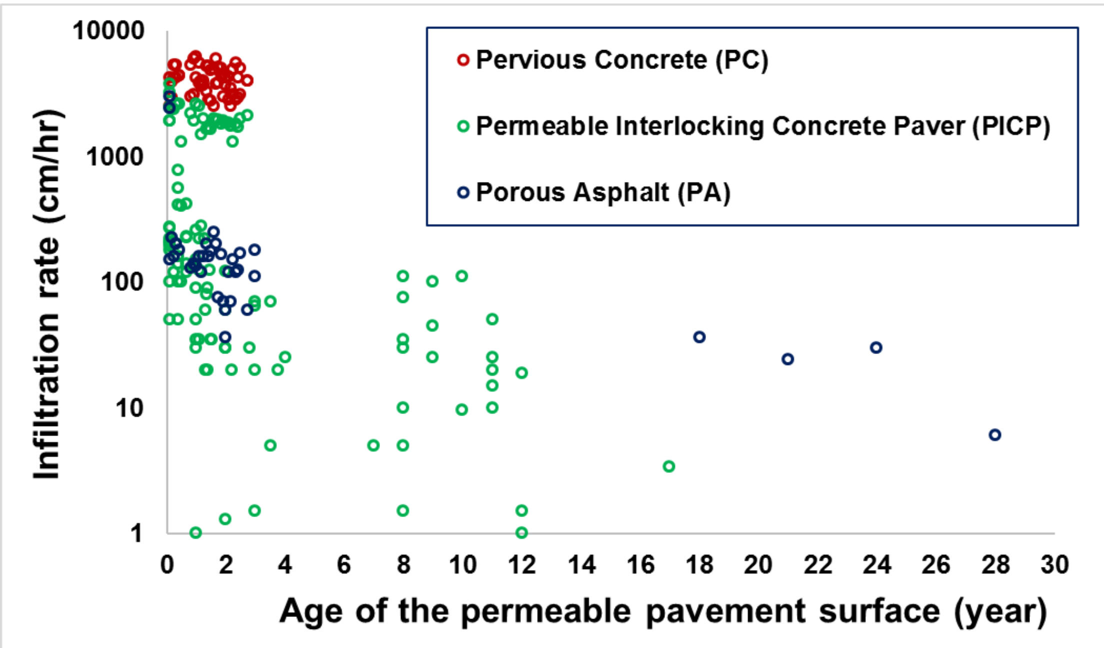
X-ray computed tomography (CT) imaging has been used to assess the clogging mechanisms of open graded friction course (OGFC) pavements [31,32]. X-ray CT images taken before and after clogging were taken on multiple core samples that were extracted from the permeable pavement sites. The images and the core profile porosities were compared and it was concluded that the clogging mainly happened in the upper layers of the pavement profiles. It was also concluded that the air temperature, rainfall depth, and size of the sediments are important factors in the clogging process.

In one previous study, a regression model was developed to predict physical clogging after a series of laboratory experiments [33]. It was concluded that clogging was highly correlated with runoff volume and flow rate. A model for clogging prediction using artificial neural networks has also been developed [34]. In this study, the peak 5-min rainfall intensity, the previous rainfall depth, and the cumulative rainfall depth from the start of the study were found to be the most effective parameters for predicting the hydrologic performance of the permeable pavement.

Laboratory tests were used to measure clogging on a length of sloping porous asphalt [24]. The results were used to develop a regression equation that was found to provide a limited and conservative estimate of clogging in a prototype scale porous asphalt pavement.

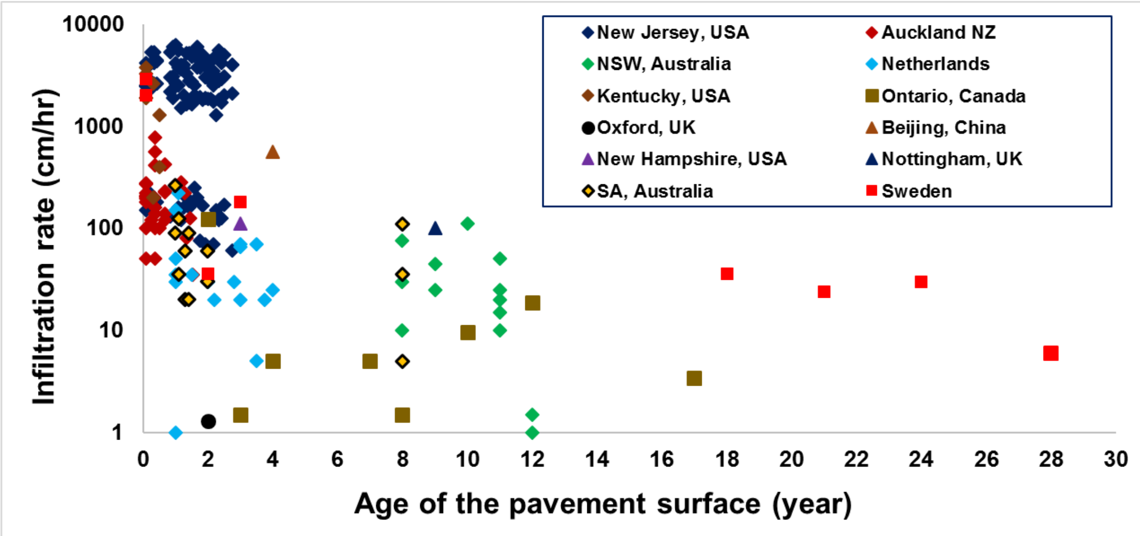
2.3. Infiltration Rate Variation with Age of Permeable Pavements

Results from several of infiltration rates studies conducted since the year 2010 were collected. The results of surface infiltration rates versus the age of the permeable pavement surface are shown in Figure 2A,B. Porous concrete (PC) showed the largest infiltration rates and this was followed by permeable interlocking concrete pavers (PICP) and porous asphalt (PA). The results also show that the infiltration rates generally reduced following the second year after installation. It is also evident from Figure 2A,B that for sites with no maintenance, after year 4 the surface infiltration rates have generally reduced to below 1000 mm/h. In some countries such as Australia, this is still an acceptable rate for pavement infiltration.



(**A**)

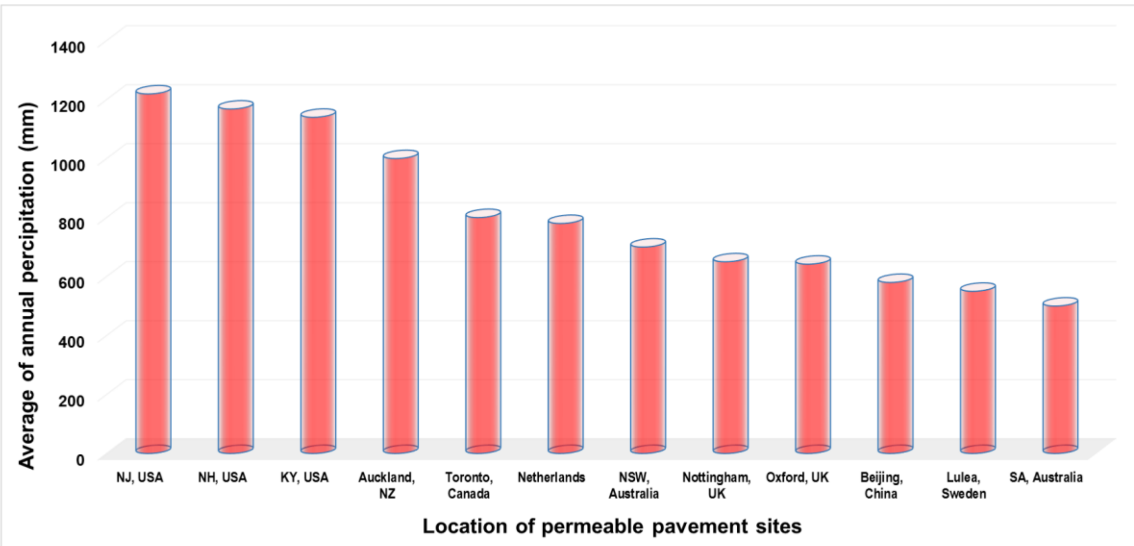
Figure 2. *Cont.*



(B)

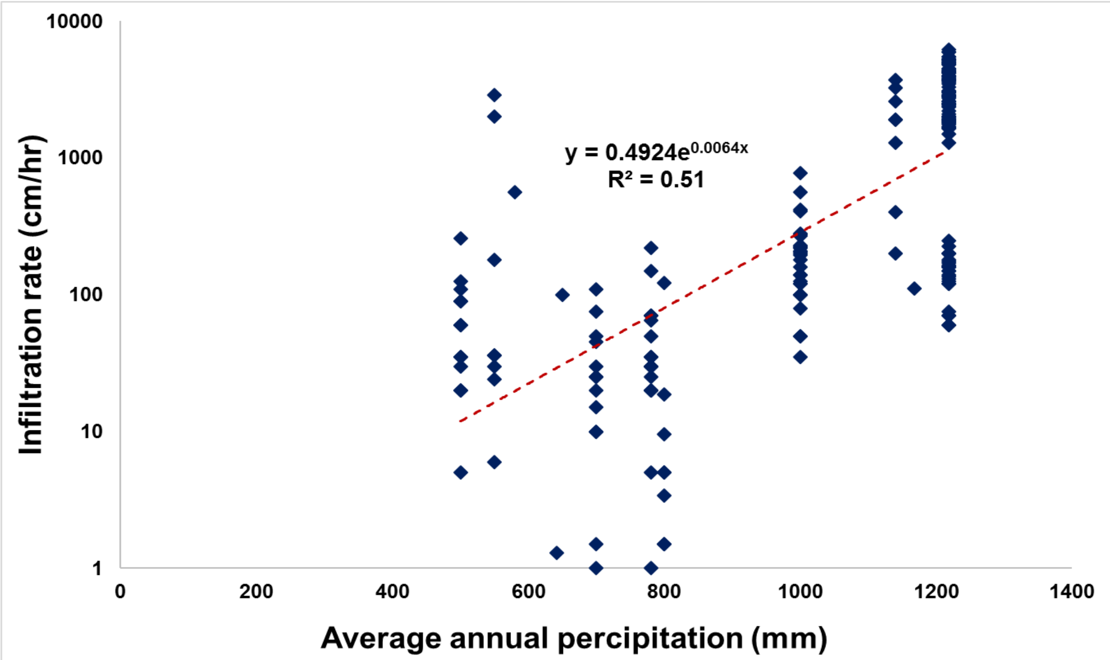
Figure 2. Effect of age of pavement on measured infiltration rates. (**A**) Infiltration rates for three pavement types; (**B**) infiltration rates for various locations. (Auckland, NZ [8], Netherlands [17], NSW, Australia [17], SA, Australia [17], Kentucky, USA [28,29], Beijing, China [35], New Hampshire, USA [35], Nottingham, UK [35], Ontario, Canada [35], Oxford, UK [35], New Jersey, USA [36], Sweden [37]).

The average yearly precipitation levels for various locations with permeable pavement sites and infiltration rates are shown in Figure 3A,B. This shows that there is a positive correlation between surface infiltration rates and ane average annual precipitation. This also supports the notion that the rainfall and its characteristics are important in the design and clogging potential of permeable pavement surfaces. It is interesting to note that most of these locations, including many cities in the US and Europe, have combined sewer systems while the Australian cities have separate urban drainage systems.



(A)

Figure 3. *Cont.*



(**B**)

Figure 3. Average annual precipitation for locations with permeable pavement sites. (**A**) Average annual precipitation and location of permeable pavement sites; (**B**) average annual precipitation and infiltration rate.

3. Maintenance

Routine maintenance is often used to keep the hydraulic performance of the permeable pavement sites within acceptable working ranges. Several studies have reported that the clogging depth only extends into the upper surface of the permeable pavement system and therefore simple cleaning of a permeable pavement upper surface can potentially return the surface infiltration capability to an acceptable level [38,39].

Several methods of maintenance, including moistening followed by sweeping, sweeping followed by suction, suction alone, and high pressure water jets combined with simultaneous suction have been examined [38]. Out of these four techniques, moistening followed by sweeping was found to have very limited success and in some cases it even increased the clogging and caused the penetration of pollutants further into the underlying aggregates.

Other maintenance techniques including manual removal of the upper 2 cm of bedding material, mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high pressure washing, and milling of porous asphalt have been investigated in a separate study [37]. The removal of the upper 2 cm of clogged material did not significantly improve the surface infiltration rates of concrete grid pavers and permeable interlocking concrete pavers. It was postulated that this was due to the inclusion of fines in the joint and bedding material during construction. For porous asphalt maintenance, industrial hand-held vacuum cleaning, pressure washing, and milling were increasingly successful at recovering the surface infiltration rate. Milling to a depth of 2.5 cm nearly restored the surface infiltration rate to like-new conditions for a 21-year old porous asphalt pavement. For PICP, street sweepers employing suction were shown to be preferable to mechanical sweepers.

In a study on porous concrete [40], it was shown how the pore network is highly complex and heterogeneous. In addition, the pore channels under the pavement are tortuous, with variable cross-sections and random interconnectivity. Tortuosity is one of the properties of a porous material usually defined as the ratio of actual flow path length to the straight distance between the ends of the flow path. Also, tortuosity is related to the inverse of connectivity. The pore structure of porous concrete and the characteristics of flowing particulates influence clogging, which occurs when particles build-up and block connected porosity. The potential for clogging is related to the tortuosity of the connected porosity, with greater tortuosity resulting in increased potential for clogging. A clogging-resistant porous concrete will require uniform pore structure with low tortuosity. Solving the problem of clogging will make porous concrete more efficient, resilient, and cost effective, thereby promoting wider use. However, the study also found that existing maintenance methods for porous concrete, such as vacuum sweeping and pressure washing, had questionable effectiveness [40].

4. Conclusions

This paper has reviewed previous studies on permeable pavement surface infiltration assessment methods, available sensors, modelling technologies, and recommended maintenance methods. There are several well-tried methods for measuring the surface infiltration rates of permeable pavement surfaces. However, these have often been adapted by researchers to save time and to develop cost effective methods to assess the performance of permeable pavement systems. The fact that many researchers and practitioners are not following standard surface infiltration testing methods because they are too complex indicates that a more efficient standard test is needed.

While the highest recorded infiltration rates are generally from high rainfall areas, the infiltration rates of permeable pavement sites in these areas declined dramatically with time. Even within two years from installation, the need for maintenance was evident at several sites. Therefore, in high rainfall areas, some researchers recommend maintenance be conducted two to four times per year. In many investigations, the assessment did not commence until the pavements were quite old and were performing poorly. There is a need to conduct infiltration tests early after installation, even if the pavement seems to be performing well.

Overall, it was evident that there is no universally superior maintenance method. Continuous monitoring of permeable pavement surfaces is necessary to better understand the in situ clogging mechanisms for a particular region. Also, developing low clogging permeable pavements should still be a high priority for both researchers and practitioners.

Conflicts of Interest: The authors declare no conflict of interest.

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