International Journal of GEOMATE, Jan., 2018 Vol.14, Issue 41, pp.159-166
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2018.41.Key3
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

USING PERMEABLE PAVEMENTS TO REDUCE THE ENVIRONMENTAL IMPACTS OF URBANISATION

Oriana Sanicola[1], *Terry Lucke[1], and Jo Devine[2]

[1]Stormwater Research Group, University of the Sunshine Coast, Australia
[2]School of Civil Engineering and Surveying, University of Southern Queensland, Australia

*Corresponding Author: Received: 28 Aug. 2017, Revised: 19 Dec. 2017, Accepted: 30 Dec. 2017

ABSTRACT: Permeable interlocking concrete pavements (PICPs) are being increasingly utilised in urban developments globally to promote stormwater infiltration, reduce catchment runoff volumes and to improve the quality of downstream receiving waters. Increased interest in permeable pavements from planners, designers and stormwater managers has led to an increase in permeable pavement research to try to address some of the common misconceptions and to investigate new research areas. This paper summarises the results of an international literature review that was undertaken to identify and examine the current state of permeable pavement research worldwide. The study found that the stormwater management and environmental benefits of permeable pavements are irrefutable and they clearly reflect the principals of low impact development. However, there are also misconceptions and barriers to their more widespread implementation which need to be addressed to ensure their future as an effective LID solution. More targeted research is required to address some of the outstanding issues with permeable pavements.

Keywords: Low impact development, Permeable pavements, Stormwater pollution, Urban runoff

1. INTRODUCTION

1.1 Low Impact Development

Altering the natural characteristics of a drainage basin through urbanisation can cause dramatic changes on the movement and storage of water within the catchment. Impervious surfaces such as roofs and pavements can prevent precipitation from reaching the soil and this can reduce infiltration and groundwater recharge. It can also increase stormwater runoff volumes and peak flowrates from the catchment. Increasing impervious areas in urban catchments can also cause flooding during periods of heavy rainfall when stormwater drainage systems are operating at capacity. Increased stormwater runoff can also cause significant reductions in downstream water quality [1, 2]. With approximately 50% of the world's population now living in urban environments impervious surface areas and their associated environmental problems are set to increase [3].

Low impact development (LID) in the USA and Japan is similar to water sensitive urban design (WSUD) in Australia, and sustainable urban drainage systems (SUDS) in Europe [4]. All of these initiatives embrace the concept of integrated land and water management and in particular, integrated urban water management [5]. The principles of LID focus on mitigating the adverse effects of urban stormwater runoff and finding solutions to integrated water cycle management. Pezzaniti et al. [5] defined these principles as being:

- Reducing portable water demand through water efficient appliance, rainwater and grey water reuse;
- Minimising wastewater generated and treatment of wastewater to a standard suitable for efficient reuse opportunities and/or release to receiving waters;
- Treating urban stormwater to meet water quality objectives for reuse and/or discharge to surface waters; and
- Using stormwater in the urban landscape to maximise the visual and recreational amenity of developments.

LID is a relatively recent concept that brings together new technologies, with an increasing interest in urban regeneration, to rethink urban water management and apply solutions to make towns and cities more sustainable.

As part of the LID stormwater management principle, a number of stormwater treatment devices have been developed to improve water quality, such as swales, bioretention basins, settlement ponds and wetlands. However, these treatment devices can require significant land uptake. Highly urbanised areas are often restricted in space, and potential stormwater treatment measures should ideally fit into the urban area without further land uptake.

Permeable pavements are one type of LID treatment device that is becoming increasingly popular globally due to the many stormwater management and environmental benefits they provide. These will be discussed in the next section.

1.2 Permeable Pavements

Permeable pavements are a relatively new technology and have quite different objectives and design requirements to conventional pavements. They can be used as an alternative to conventional impervious hard surfaces, such as roads, carparks, footpaths and pedestrian areas [6].

Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and structure where it is filtered through the various pavement layers. The filtered stormwater is then either harvested for later reuse or released slowly into the underlying soil or stormwater drainage system [6]. This results in many stormwater management and environmental benefits. The most common type of permeable pavement is the permeable interlocking concrete paving (PICP) system shown in Fig. 1 [2].

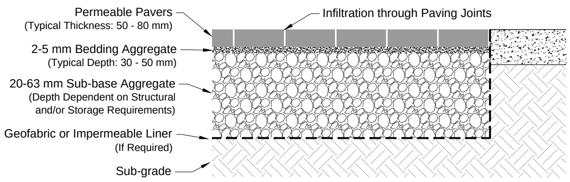

Fig. 1 Typical PICP Schematic

Even for PICP systems not designed for harvesting and reuse, the storage capacity in the basecourse layers (Fig. 1) can be designed to intercept significant rainfall events. PICPs can therefore reduce runoff volumes and discharge rates from paved surfaces [8-10]. These reductions result in a significantly reduced risk of downstream flooding. PICPs also provide considerable water quality improvements by treating and trapping stormwater pollutants [11, 13].

PICPs are one LID treatment option that do not require any increase in land area. They help increase infiltration in urbanised areas and help reduce pressure on existing stormwater infrastructure. They are commonly used as part of a treatment train or as a source control measure [5]. Permeable pavements in good working order have infiltration rates, from 130 mm/h up to several thousand mm/h [2, 14, 20] and can manage the runoff of rainfall events in excess of a 1 in 100-year storm event [15].

However, the performance of a PICP system also depends on the local site conditions. For example, if underlying soils have low permeability a collection pipe is often needed in the base of the system to divert infiltrated water to the underground drainage network.

Permeable paving provides multiple benefits for managing stormwater runoff at source [2]. They help to reinstate the infiltration capabilities and restore the natural hydrological cycle of urban areas which reduces runoff volumes and the risk of flooding. They filter and treat the infiltrating runoff by trapping pollutants that might otherwise contaminate groundwater and stormwater [2, 16]. It is also thought that permeable pavements can reduce the urban heat island effect and can contribute to a wider range of sustainable water management objectives through rainwater harvesting [6, 17]. Recent research [18, 19] has also shown that the ability of permeable pavements to allow water and air to infiltrate through to the root zone can significantly improve street tree health and minimize pavement damage.

However, there are some common misconceptions associated with the use of permeable pavements systems. These include the belief that they cannot be used in clay soils, that they clog easily which hinders infiltration, and that they do not work well in cold climates due to damage caused by freeze and/or frosting [22]. There are also numerous permeable pavement design guidelines in use worldwide and that the information contained in these design guidelines is often unclear and occasionally conflicting. These issues may have hampered the more widespread implementation of permeable pavement systems.

Increased interest in permeable pavements from planners, designers and stormwater managers has led to an increase in permeable pavement research to try to address some of the common misconceptions [2, 4, 5, 20, 21]. It has also initiated new research areas such as using permeable pavement for stormwater harvesting and reuse and to promote street tree health [6, 18, 19, 22, 23].

This paper summarises the results of an international literature review that was undertaken to identify and examine the current state of permeable pavement research worldwide. It is intended as a practical resource for designers and researchers of permeable pavement systems.

2. INTERNATIONAL PERMEABLE PAVEMENT RESEARCH

2.1 Clogging

2.1.1 Porous Pavements

Research has shown that urban stormwater runoff contains significant concentrations of suspended sediments and gross pollutants [2, 8, 20, 24]. There is a perception that permeable pavements that are used as source control devices, and designed to infiltrate runoff, will tend to clog quickly and result in high maintenance and replacement costs. This perception has led to a steady increase in the number of research studies into the clogging processes that take place in permeable pavements [4, 5, 21, 24-27].

Much of the earlier clogging research was conducted on porous concrete materials which have different clogging processes to PICPs [28-31]. The research tended to show that porous pavement materials were more susceptible to clogging, and more difficult to maintain than other systems and their popularity has declined over the last decade.

However, new pavement designs presented by Dierkes et al. [32] demonstrated success with a double layer concrete paver with an impermeable top layer and a porous base layer. The study found that the new pavers could temporarily store water close to the surface which helped promote evaporation of the water back into the atmosphere. This process could help reduce heat island effects. The new paver design was found to be less prone to clogging and the impermeable top layer was also found to be more resistant to damage than typical porous layers. Further research is currently underway to evaluate the new paving design under operational conditions.

2.1.2 PICPs

A significant amount of research has now have been published on the clogging processes that take place in PICPs and the subsequent effects these have on hydraulic performance and how these processes change over time [2, 4, 5, 20, 21, 26]. The key mechanisms that govern clogging in different systems are also now better understood than they were a decade ago.

Pratt [40] undertook a laboratory investigation on small scale, full-size pavement models to investigate pollutant retention within the permeable pavement structure. This study appears to be the first to use an accelerated stormwater sediment dosing program to simulate the long-term performance of PICPs due to clogging. Pratt [40] found that most of the sediment and organic materials tends to get trapped in the upper layers of the bedding aggregate and on the geofabric filter and this prevents them migrating through to the basecourse materials. Pratt predicted that this will lead to eventual total clogging of the system suggesting an effective life span of between 15 and 20 years in service [40].

Borgwardt [24] reported on the long-term, in-situ infiltration performance of PICPs and presented infiltration test results for over 80 test locations. Borgwardt [24] maintained that the infiltration performance of PICPs decreases significantly within a few years of service due to the entrainment of mineral and organic sediment material retained in the upper 20 mm of the pavement joint material. Comparisons of PSD analyses showed that there were 26% (by mass) more fine particles (less than 63 µm in diameter) trapped in the upper 20 mm of the joint material than in the lower 20 mm. Borgwardt [24] predicted that in practice, the permeability of PICP systems reduces to approximately 18% of the original infiltration value after approximately 10 years' service.

Research to improve understanding of the long-term hydraulic conductivity and the clogging processes in permeable pavements was undertaken by Pezzaniti et al. [5]. The focus of the study was to quantify the degree of sediment trapping and associated pollutant retention in order to assess the effective life of PICPs. For their laboratory experiments, Pezzaniti et al. [5] applied locally sourced stormwater sediment to PICP testbeds, similar in construction to those used by Pratt [40], in order to simulate 35 years of sediment loading. The study [5] concluded that there are two types of sediment accumulation involved in the clogging process of PICPs, namely coarse and fine sediments. They explained that coarse sediment is retained in a relatively small upper horizon of the pavement joints and this can reduce fine sediment migration to the lower layers. This generally supported by previous research studies [12, 24, 40].

Fassman and Blackbourn [41] investigated infiltration rates and clogging of a 200 m^2 PICP site that was constructed to form part of a main arterial road in Auckland, New Zealand. The structure was made from PICP blocks (with wide gaps) on a 2 to 5 mm aggregate bedding layer. A geofabric layer was included between the bedding layer and the basecourse. Sub-surface investigations beneath the pavers revealed that a crust had formed above the geofabric and that some of the bedding layer had formed into agglomerated chunks. This in an important finding [41] and demonstrates the significant role that dry periods of no rainfall play in the sediment retention and clogging processes that potentially occur in PICPs. This finding suggests that results from simulated long-term sediment loading studies that do not include drying cycles, may not be applicable to prototype PICP field installations.

Lucke and Beecham [2] undertook a forensic investigation on a clogged eight-year-old PICP system to determine how sediment had accumulated within the pavement structure. They found that most of the sediment was trapped in the gaps between the paving blocks and on top of the bedding aggregate directly below the gaps. The sediment accumulation pattern that took place on the bedding aggregate beneath pavers is shown Fig. 2. This clearly demonstrates the effectiveness of the bedding aggregate as a filter medium to remove sediment from stormwater runoff.

Fig. 2. Sediment Accumulation Pattern on Bedding Aggregate [2]

It is also clear from Fig. 2 that sediment is only deposited on the bedding aggregate directly below the paving joints. The rest of the bedding aggregate is effectively "as new" and has performed no sediment removal function at all. This suggests that the PICP design is not fully utilising the filter medium properties of the bedding aggregate. Therefore, it was hypothesised [2] that there may be a more effective PICP design which makes greater use of the bedding aggregate area to filter more sediment from stormwater runoff. This was investigated and described below [21].

The studies outlined above demonstrate the variability of findings from previous research into the clogging processes that occur in permeable pavements and the effects that these processes have on the long-term viability of these systems. While a number of the studies have examined the sediments accumulated in the paving layers in some detail, most of this research did not examine the clogging processes experienced by sediment particle sizes less than 63 µm in diameter. Those studies that did look at particle sizes of less than 63 µm in diameter were conducted on laboratory models and these results may not be applicable to prototype PICP field installations. Further research is required to better understand this process.

2.2 Infiltration

Adequate infiltration through PICPs is critical to their hydraulic and stormwater treatment performance. Infiltration is affected by clogging caused by the trapping of fines in the PICP surface, which, over time, reduces treatment performance. It has been shown that clogging can be reduced by periodic maintenance such as vacuum sweeping and/or pressure washing. It has also been suggested that a PICP's maintenance requirements can be identified by measuring reduced infiltration rates. This section examines some of the previous research on PICP infiltration.

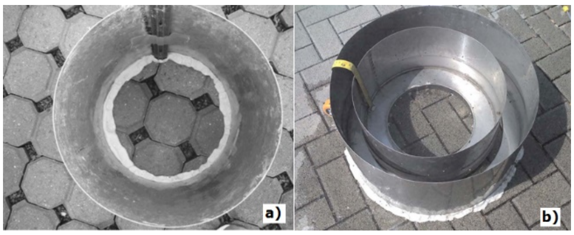

Fig. 3. Modified Ring Infiltrometers for Permeable Pavement Testing with Waterproof Sealant (a) Single Ring; (b) Double Ring [27]

Bean et al. [9] evaluated the surface infiltration rates of 40 permeable pavement sites in North Carolina, USA. They measured the surface infiltration rates of different permeable pavement types and tried to relate the infiltration performance to paver type. They used both the Single-ring infiltrometer test method [42] and the Standard test method for infiltration rate of soils in field using double-ring infiltrometer [43] in their study (Fig. 3).

The study [9] measured infiltration rates between 1,000 mm/h and 40,000 mm/h for PICPs that were not blocked with fine particles. However, the infiltration rate of PICPs that were partially filled by fine soil particles reduced to between 16 mm/h and 2,000 mm/h. They concluded that PICP sites installed for infiltration purposes should not be located adjacent to areas with disturbed soils as accumulations of fine particles can dramatically decrease surface infiltration rates. They also found that higher surface infiltration rates could be sustained by using a vacuum sweeper at regular intervals for maintenance [9].

Lucke and Beecham [2] investigated the infiltration performance of a PICP system that has been in service for over eight years. They developed a new type of double ring infiltration testing apparatus that measured the surface infiltration rate over one full square metre (1 m2) of paving (Fig. 4). They also found that different areas of the PICP were affected by blockage by fine soli particle and they classified the different areas as either, Fully Blocked (FB), Medium Blocked (MB) or Unblocked (UB).

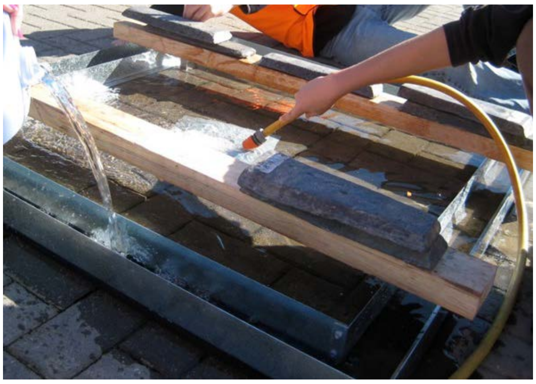

Fig. 4 Double-ring Infiltration Testing Apparatus Developed by [2]

They [2] found the average infiltration rates for the pavement to be 11 mm/h for the FB areas, 165 mm/h for the MB areas, and 8,530 mm/h for the UB areas. They found that although there was only a maximum difference of 56% in the mass of sediments retained in the paving layers, the infiltration rates varied by five orders of magnitude. These results reinforced previous research findings on the importance of maintaining PICPs to ensure effective surface infiltration rate performance.

Due to the difficulty and inconsistencies experienced with PICP infiltration testing using traditional methods, two new experimental test procedures were developed and evaluated [27] to more accurately determine the surface infiltration rate of PICPs. The two new methods were the falling head full-scale (FHFS) method and the constant head full-scale (CHFS) method. Both of the new methods involved inundating a large area of the pavement in order to determine the infiltration rate through the pavement surface (Fig. 5). Double ring infiltrometer tests were also performed to enable a comparison of the results to traditional methods.

While the new infiltration testing methods [27] were found to be more reliable and consistent than traditional methods, there was still a large variation in the results during the testing. It was found that moisture levels in the soil underneath the PICP installation significantly affected test results. This was particularly apparent when multiple tests were performed at the same site as infiltration rates decreased as more tests were performed. Overall, the study [27] found that the new falling head full-scale testing method produced the most accurate results. This study is continuing the new method has been applied to numerous sites across Europe. It is anticipated that the full results of this study will be published in the near future.

Fig. 5 - Full-scale Infiltration Testing in the Netherlands [27]

Lucke et al. [44] compared infiltration results using the standard test (C1781M-14a – Fig. 3a) with the results of a new stormwater infiltration field test (SWIFT – Fig. 6) developed in Australia to evaluate the maintenance requirements of PICPs.

Fig. 6. Stormwater infiltration field test (SWIFT) Infiltrometer used in this study. (a) SWIFT in use; (b) SWIFT dimensions [44].

A strong correlation was found between results using the two methods. The study found that the SWIFT was a reliable method for estimating the degree of clogging of PICPs while successfully overcoming some of the problems with the more technical existing test methodology such as horizontal water leakage (use of sealant), unrealistic pressure heads, speed of test, and portability. The SWIFT test [44] is a simple, fast and inexpensive way for asset managers and local government employees to quickly assess the maintenance requirements of PICP installations in the field.

2.3 Sediment Slots

Previous PICP clogging research [2] demonstrated that sediment is only deposited on the bedding aggregate directly below the paving joints. The rest of the bedding aggregate is effectively "as new" and has performed no sediment removal function at all. This suggested that current PICP designs were not fully utilising the filter medium properties of the bedding aggregate. It was therefore hypothesised that there may be a more effective PICP design which makes greater use of the bedding aggregate area to filter more sediment from stormwater runoff.

Fig. 7 – Sediment Slots Being Cut into Underside of PICP blocks [21]

A proof of concept study [21] was performed to investigate more efficient use of the bedding aggregate used in PICP systems. Lateral drainage channels (sediment slots) were cut into the underside of PICP blocks (Fig. 7) to allow sediment-laden stormwater to access, and be treated by, a greater surface area of bedding aggregate. Eight different slot designs (Fig. 8) were trialled in the study [21].

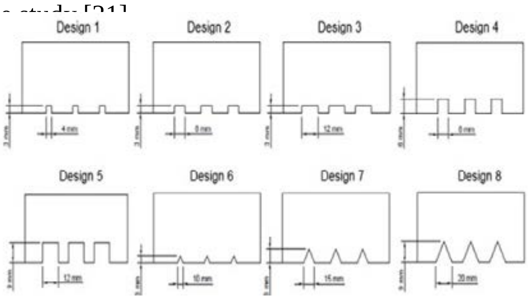

Fig. 8 - Eight Different Drainage Slot Designs Trialled in Study [21]

Specially fabricated PICP models were tested in the laboratory using semi-synthetic stormwater to determine which of the slot designs made the most efficient use of the bedding aggregate to filter the sediment from the stormwater.

The study [21] results (Fig. 9) clearly demonstrated that the eight drainage slot designs deposited between 25% and 366% more sediment beneath the pavers than the control pavement (Design 9). The results of the study [21] strongly suggest that PICP systems with drainage slots cast into their bases would take much longer to clog than unmodified pavers, thereby proving the initial concept of this study. However, more research would be required to verify this fully. More research is also required to optimise the drainage slot designs for use on different paver bedding materials. Finally, a better method of quantifying the amount of sediment that is deposited on the bedding aggregate needs to be developed.

Fig. 9. Study Sediment Distribution Patterns

2.4 Summary

Altering the natural characteristics of a drainage basin through urbanisation can impose dramatic changes on the movement and storage of water within the catchment. As permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and structure they can be used to promote infiltration and groundwater recharge, while decreasing stormwater runoff volumes and flowrates from the catchment. The use of permeable pavements can result in many stormwater management and environmental benefits.

The preceding sections have outlined some of the latest international permeable pavement research studies. While there have been other quality studies undertaken, the majority of the research tends to focus on issues to do with surface infiltration and clogging. The stormwater management and environmental benefits of permeable pavements are undeniable and they clearly reflect the principals of low impact development. Uncertainties surrounding surface infiltration and clogging are clearly the main barrier to the more widespread implementation of permeable pavements. If these issues can be satisfactorily addressed, the future of permeable pavements will be assured.

3. CONCLUSION

This review of permeable pavement research has identified a number of potential solutions to the issues surrounding clogging and reduced surface infiltration capacities. These include:

- A new PICP design using a double layer concrete paver construction with an impermeable top layer and a porous base layer. The new paver design was found to be less prone to clogging, better at evaporating water back into the atmosphere, and more resistant to damage than typical porous layers.
- PICP sites installed for infiltration purposes should not be located adjacent to areas with disturbed soils as accumulations of fine particles can dramatically decrease surface infiltration rates.
- Higher surface infiltration rates can be sustained by using a vacuum sweeper at regular intervals for maintenance.
- Research suggests that PICP's maintenance requirements can be identified by measuring reduced infiltration rates. A number of new methods for measuring surface infiltration capacity were examined.
- New infiltration rate testing methods involving inundating large areas of the pavement were found to be more reliable and consistent than traditional methods, although they were more difficult to implement.
- The SWIFT test is a simple, fast and inexpensive way for asset managers and local government employees to quickly assess the maintenance requirements of PICP installations in the field.
- A proof of concept study to investigate more efficient use of the bedding aggregate used in PICP systems was examined. The study results strongly suggest that PICP systems with drainage slots cast into their bases would take much longer to clog than unmodified pavers.

While all of the potential solutions listed above may be able to resolve some of the issues surrounding surface infiltration and clogging to some extent, more targeted research is required to explicitly address the uncertainties surrounding permeable pavement performance. More positive research results that demonstrate the potential benefits of permeable pavements will secure their future in the LID integrated land and water management philosophy.

4. REFERENCES

[1] Dietz, M.E. Low impact development practices: a review of current research and recommendations for future directions. *Water Air Soil Pollution*. 186, 2007, 351-363.

[2] Lucke, T., Beecham, S. Field investigation of clogging in a permeable pavement system. *Building, Res. & Inform*. 39(6), 2011, 603-615.

[3] Mullaney, J. and Lucke, T. Practical Review of Pervious Pavement Designs. *CLEAN - Soil, Air, Water Journa*l, 42(2), 2014, 111–124.

[4] Boogaard, F., Lucke, T. and Beecham, S. Effect of Age of Permeable Pavements on Their Infiltration Function. *CLEAN - Soil, Air, Water Journal*, 42(2), 2014a, 46–152.

[5] Pezzaniti, D., Beecham, S. and Kandasamy, J. Influence of clogging on the effective life of permeable pavements, *Journal of Water Management*, 162(2), 2009, 76-87.

[6] Beecham, S., Lucke, T. and Myers, B. (2010) Designing porous and permeable pavements for stormwater harvesting and reuse, in Proceedings of 1st European IAHR Congress, Edinburgh, UK.

[7] Pratt, C.J., Mantle, J. and Schofield, P. UK Research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality, *J. of Water Sci. & Tech*., 32(1), 1995, 63-69.

[8] Hunt, B., Stevens, S. and Mayers, D. Permeable pavement use and research at two sites in eastern North Carolina, in Proceedings of the 9th International Conference on Urban Drainage, Portland, Oregon, 2002, USA.

[9] Bean, E., Hunt, W. and Bidelspach, D. Field survey of permeable pavement surface infiltration rates, *Journal of Irrigation and Drainage Engineering*, 133(3), 2007, 247-255.

[10] Collins, K., Hunt, W. and Hathaway, J. Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina, *Journal of Hydrologic Eng*., 13(12), 2008, 1146-1157.

[11] Pratt, C.J., Mantle, J. and Schofield, P. Urban stormwater reduction and quality improvement through the use of permeable pavements, *Journal of Water Sci. and Tech*., 21(8), 1989, 769-778.

[12] Dierkes, C., Angelis, G., Kandasamy, J. and Kuhlmann, L. Pollution retention capability and maintenance of permeable pavements, in Proceedings of the 9th ICUD Conference, IWA, Portland, Oregon, 2002, USA.

[13] Brattebo, B. and Booth, B. Long-term stormwater quantity and quality performance of permeable pavement systems, *Journal of Water Research*, 37(18), 2003, 4369–4376.

[14] Volder, A. Watson, T. and Visawanathan, B. Potential use of pervious concrete for maintaining existing mature trees during and after urban development. *Urban Forestry and Urban Greening*. 8(4), 2009,249-256.

[15] Shaffer, P., Wilson, S., Brindle, F., Baffoe-Bonnie, B., Prescott, C., Tarbet, N. Understanding permeable and impermeable surfaces-technical report on surfacing options and cost benefit analysis. 2009, London, Dept. for Communities and local Government.

[16] Sansalone, J., Kuang, X., Ranieri, V. Permeable pavement as a hydraulic and filtration interface for urban drainage. *J. Irrig. Drain. Eng*. 134(5), 2008, 666-674.

[17] Frazer, L. Paving paradise-the peril of impervious surfaces, *Environmental. Health Perspectives*. 113(7), 2005, 457-462.

[18] Mullaney, J., Lucke, T. and Trueman, S.J. A review of benefits and challenges in growing street trees in paved urban environments, *Landscape & Urban Plan*., 134, 2015a, 157–166.

[19] Mullaney, J., Lucke, T. and Trueman, S.J. The effect of permeable pavements with an underlying drainage layer on the growth and nutrient status of urban trees. *Urban Forestry & Urban Greening*, 14(1), 2015b, 19-29.

[20] Boogaard, F., Lucke, T., van de Giesen, N. and van de Ven, F. Evaluating the Infiltration Performance of Eight Dutch PPs Using a New Full-Scale Infiltration Testing Method. *Water*, 6(7), 2014b, 2070-2083.

[21] Lucke, T. Using Drainage Slots in Perm. Paving Blocks to Delay the Effects of Clogging: Proof of Concept Study. *Water*, 6(9), 2014, 2660-2670.

[22] Morgenroth, J. and Visser, R. Above-Ground Growth Response of Platanus orientalis to PPs, *Arboric. Urban Forestry*, 37(1), 2011,1–5.

[23] Morgenroth, J., Buchan, G. and Scharenbroch, B.C. Belowground Effects of Porous Pavements – Soil Moisture and Chemical Properties, *Journal of Ecological Eng*., 51, 2013, 221–228.

[24] Borgwardt, S. Long-term in-situ infiltration performance of permeable concrete block pavement, in Proceedings of 8th ICBP, San Francisco, 2006, USA.

[25] Colandini, V., Legret, M., Brosseaud, Y. and Baládes, J.D. Metallic pollution in clogging materials of urban porous pavements, Journal of *Water Sci. and Technology*, 32(1), 1995, 57-62.

[26] Yong, C.F., Deletic, A., Fletcher, T.D. and Grace, M.R. The drying and wetting effects on clogging and pollutant removal through porous pavements, in Proceedings of 7th International Conference, NOVATECH 2010, Lyon, France.

[27] Lucke, T., Boogaard, F. and van de Ven, F. Evaluation of a New Experimental Test Procedure to More Accurately Determine the Surface Infiltration Rate of Permeable Pavement Systems. *Urban Planning and Transport Research*, 2(1), 2014, 22-35.

[28] Hogland, W., Larson, M. and Berndtsson, R. The pollutant build-up in pervious road construction, in Proc. 5th ICUD, Osaka, Japan, 1990, 845-852.

[29] Larson, R. Swedish experience with design and construction of pervious asphalt constructions, in Proceedings of the Standing Conference on Stormwater Source Control, Volume I, Ed. C.J. Pratt, Coventry University, 1990, UK.

[30] Legret, M. and Colandini, V. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals, J. of *Water Sci.& Tech*., 39(3), 1999, 111-117.

[31] Raimbault, G., Nadji, D. and Gauthier, C. Stormwater infiltration and porous material clogging, in Proceedings of the 8th ICUD, Sydney, Australia, 1999, 1016-1024.

[32] Dierkes, D., Lucke, T., Hulsman, H., Vergroesen, T. Permeable pavements as effective method to restore the urban water balance. IWA Water Week, 8-11th July, 2016, Singapore

[33] Pratt, C.J. Permeable pavements for stormwater quality enhancement, in Proceedings of Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined Sewer Tech., Ed. H.C. Torno, ASCE, 1990, 131-155.

[34] Fassman, E. & Blackbourn, S. Urban runoff mitigation by a PP system over impermeable soils, *J. Hyd. Eng*. 15(6), 2010, 475-485.

[35] American Standard Testing and Materials (ASTM). Standard test method for surface infiltration rate of permeable unit pavement systems; C1781/C1781M-14a; ASTM International: PA, USA, 2014.

[36] American Standard Testing and Materials (ASTM). Standard test method for infiltration rate of soils in field using double-ring infiltrometer. ASTM D 3385, ASTM International: PA, USA, 2014.

[37] Lucke, T., White, R., Nichols, P.W.B. and Borgwardt, S. A Simple Field Test to Evaluate the Maintenance Requirements of Permeable Interlocking Concrete Pavements. *Water*, 7(6), 2015, 2542-2554.