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ADDRESSING THE DEMANDS OF THE NEW GERMAN PERMEABLE PAVEMENT DESIGN GUIDELINES AND THE HYDRAULIC BEHAVIOUR OF A NEW PAVING DESIGN

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Abstract

Permeable Interlocking Concrete Pavers (PICP) are a relatively new type of Sustainable Urban Drainage System treatment technology that has become increasingly popular in recent years to mitigate the consequences urbanisation such as increased stormwater runoff volumes and pollution loads, increased risk of downstream flooding and increased heat island effects. In Germany, PICPs have suffered damage due to severe climatic conditions over the last few decades and new regulations have now been introduced to minimise future damage. The new regulations stipulate that PICPs with porous top surfaces may no longer be used and stormwater must now be infiltrated through the joints between PICP pavers. In addition, new German guidelines have been introduced that specify the type of materials allowed to fill the joints of PICPs. This paper describes and presents the results of an experimental investigation that was undertaken on six different PICP structures to evaluate the hydraulic behaviour and determine the most effective joint filling and bedding materials for PICP systems in Germany.

Keywords: PICP, Stormwater runoff, Stormwater infiltration, Stormwater pollution.

1. Introduction

It is widely accepted that urbanisation leads to an increase in the area of land covered by impervious surfaces including rooftops, roads, driveways and car parking areas [1-3]. The consequences of this include increases in stormwater runoff volumes and stormwater pollution loads [4], as well as increased risk of downstream flooding and increased heat island effects [5]. One of the major consequences of reduced natural infiltration through urbanisation is an increase in

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Abbreviations

DIBt	Deutsches Institut für Bautechnik
PICP	Permeable Interlocking Concrete Pavements
SUDS	Sustainable Urban Drainage Systems
TN	Total nitrogen
TP	Total phosphorous
TSS	Total suspended solids
WSUD	Water sensitive urban design

localised flooding. The increased volumes of stormwater from urban developments are often simply diverted into existing stormwater and sewer systems and this frequently exceeds their capacities leading to local flooding. A lack of groundwater for evaporation can also result in a hotter, drier climate in urban areas. This is known as Urban Heat Island Effect. In addition, pollutants from traffic and other anthropogenic activities in urban areas can compromise the quality of groundwater and receiving waters.

In recent years, the management and treatment of stormwater runoff from urban areas has become a priority issue for those responsible for planning, construction and maintenance of new and refurbishment of existing urban developments. The relatively recent initiative of water sensitive urban design (WSUD) in Australia (also known as SUDS in the UK; LID in the USA) has arisen in response to the need to address water and stormwater issues related to urban developments. WSUD is the integration of urban planning and management practices to protect and conserve the urban water cycle and ensure that urban developments are sensitive to natural hydrological and ecological processes [6, 7].

In Germany, the results of expanding urbanisation are causing serious environmental problems in the area of stormwater management. The increased volumes of stormwater from urban developments are often simply diverted into existing stormwater and sewer systems and this frequently exceeds their capacities leading to local flooding. This situation is expected to become even more problematic in future due to expected climate change. Research indicates that the intensity of the summer rainfall in Germany will increase substantially. Therefore, sustainable solutions for handling stormwater that more closely represent the natural water cycle are urgently required in Germany.

Pavements currently account for approximately 25% of impervious areas within urban environments [8]. Typically two-thirds of all the rain that falls on potentially impervious surfaces in urban catchments ends up on pavements [9]. Pavements generate significant volumes of runoff which is often contaminated with sediment, heavy metals and hydrocarbons [10, 11].

Permeable pavements are a relatively new type of SUDS treatment technology that has become increasingly popular in recent years due to the many environmental and stormwater management benefits they provide. Permeable pavements generate less stormwater runoff than conventionally constructed pavements and improve stormwater quality via a combination of detention and filtration processes [12, 13]. 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 [14]. While the capacity of existing sewers in Germany can generally satisfactorily handle runoff volumes from rainfall events of up to approximately 50 mm/h, permeable pavers can easily infiltrate more than 500 mm/h.

Permeable pavements 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 [15]. The use of permeable pavements in place of traditional impervious surfaces addresses many of the stormwater management principles targeted by SUDS initiatives. Permeable pavements can also increase evaporation rates by 16% compared to traditional pavements [16].

However, permeable pavements are not utilised as often as they could be in Germany, or in the rest of the world. One potential reason for the low utilisation rate of permeable paving systems is the stark industrial look that many of the traditional paving systems have. Traditional permeable paving systems often do not meet the design demands of landscape architects and designers. Many also have important disadvantages like wide infiltration joints that can cause structural damage to the surface and are not practical for high heels or shopping trolleys, etc.

The function of permeable pavements more closely replicates the natural hydrological cycle than other technical SUDS devices. Permeable pavement construction methods are similar to those of traditional concrete block pavements. However, in contrast to traditional pavements, permeable pavements are specifically designed to allow stormwater to infiltrate through the pavement surface and into the various pavement layers and the soil below (Fig. 1).

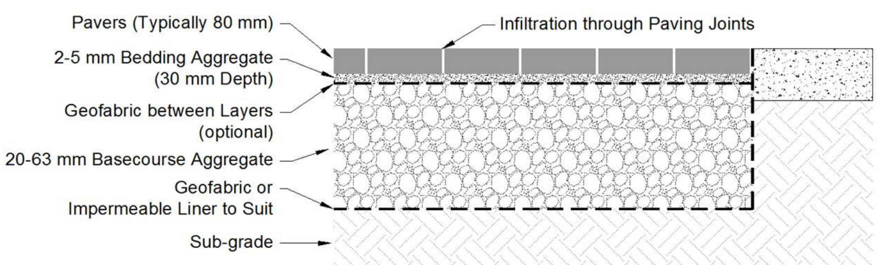
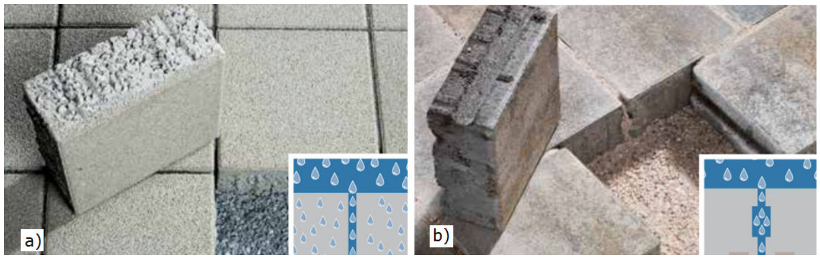


Fig. 1. Typical Permeable Pavement Structure.

There are generally two different types of permeable pavements used in Germany: Porous Pavements, Fig. 2(a), where the paving blocks are fabricated from porous concrete containing open pores to allow water to pass through it; and Permeable Interlocking Concrete Pavements (PICP), where the paving blocks are fabricated using normal concrete and the stormwater is allowed to infiltrate through the joints between the pavers and into the structure below, Fig. 2(b).



(a) Porous Pavement **(b) PICP**

Fig. 2. Types of Permeable Pavements Used in Germany.

Porous pavements and PICPs remove pollutants from stormwater runoff by allowing it to infiltrate through the paving surface where it is filtered through the various layers. Therefore most of the treatment occurs through physical (or mechanical) processes. Mullaney and Lucke [5] have shown that permeable pavements can effectively remove a variety of pollutants from stormwater including total suspended solids (TSS), total phosphorous (TP), total nitrogen (TN), heavy metals and motor oils. These pollutants become trapped within the void spaces of the different pavement materials during stormwater infiltration. Heavy metals are known to adhere to the fine sediment particles [17], and naturally occurring chemical processes and micro-organisms break down hydrocarbons and nutrients [18].

In the case of PICPs, the joints between the pavers are not filled with sand or other binders as they are with conventional pavers. PICPs are designed so that there is a significant open space between the pavers to allow water to infiltrate into the pavement structure, as shown in Fig. 2(b). This is either achieved by way of specially designed paving shapes that include small apertures in the paving surface or with slots or spacing lugs that are cast into the perimeter of the pavers. The joints and open spaces between the pavers are often filled with an appropriate joint filler material which promotes rapid infiltration into the pavement structure while trapping sediment and other pollutants.

Permeable pavements in Germany are typically designed with a connected surface/treatment area ratio of 1:1. This can significantly increase groundwater infiltration rates while reducing downstream runoff volumes and associated flood risk [15]. Permeable pavements can also increase evaporation rates thereby helping to restore the natural hydrological cycle. While permeable pavements can produce significant environmental benefits, their design and planning requires advanced technical knowledge and should only be undertaken by experienced designers. The highest water quality security can be achieved by using only officially approved systems [19].

PICPs have had some severe problems under German climatic conditions over the last few decades. Frost periods and the use of de-icing salts have been found to attack the structure of the porous concrete paving stones. Even when manufacturers recommend not to use de-icing salts on porous pavements many councils and local government authorities still use salt due to perceived safety concerns. The salt damage problems were exacerbated in 2013 because de-icing salts with higher CaCl content (>95%) were imported. The increased levels of CaCl attacked the concrete and the degree of damage to some pavements was often unacceptable and needed to be replaced.

Due to the degree of salt damage that PICPs sustained in the past, new permeable pavement systems were required that only infiltrated stormwater through the joints. In addition, new German guidelines have been introduced that specify the type of materials allowed to fill the joints of PICPs. This paper describes and presents the results of an experimental investigation that was undertaken to evaluate and determine the most effective joint filling and bedding materials for PICP systems in Germany.

2. New PICP Paver Development

Typical PICP systems achieve their high infiltration capacity by using unusually wide joints with a coarse joint filling material in their design. However, new German paving regulations have set a maximum allowable joint width of 6 mm for PICP paving stones with a thickness of up to 80 mm. As pavements with small joints are extremely sensitive to clogging processes, a new solution had to be developed.

The main idea for the new PICP system was to use a paving stone with two layers, a typical concrete top layer of 10 mm and a 70 mm base layer made from porous concrete. That way, the advantages of a porous system could be combined with a classic surface layer that is resilient to frost and de-icing salts. Figure 3 shows a prototype of the new paving stone where the impermeable top layer and the porous base layer, where the water can be transported towards the sub-base, is shown.

Fig. 3. Newly Developed PICP Paving Stone.

The new PICP system provided a solution to one of the main problems with typical joint infiltration systems. When the joint material is clogged in normal PICP systems, it must be replaced. Generally it is only possible to replace the uppermost 20 to 30 mm of joint filler material [20, 21]. If the lower part of the joint filling material is still clogged, the system cannot be properly maintained and it remains at least partially clogged. However, for the newly developed PICP system, replacing only the top 20 to 30 mm has been found to be adequate because from that depth the water van percolate through the porous concrete and so the porosity of the total system is much higher.

The permeability of PICPs is known to reduce significantly due to clogging during the first years of operation [20]. A newly constructed PICP system must infiltrate at least 194 mm/h according to German regulations [22] while older pavements must be able to infiltrate an average of at least 97 mm/h. If the infiltration capacity is found to be lower than this, the PICP must be maintained and/or cleaned. Taking into account a decline of up to 66 % in the first years [23], the required initial infiltration capacity should probably be at least 300 mm/h for a new pavement to ensure that the PICP will operate satisfactorily for a sufficient period without the need of maintenance.

In the past, a hard split rock (2 to 5 mm in diameter) was often used for the bedding layer of PICPs. However, this no longer conforms to the new guidelines and regulations in Germany. Bedding materials without fines may no longer be used. Bedding layer requirements are given in the European standard DIN EN 13285, the German Technical Delivery Standard - StB 04 Annex H and the German TL Pflaster – StB 06. Since the paving joints have a stabilising affect for the pavements, the crushing strength of the joint filling materials must also be very high. Soft aggregates can be crushed in the joints and this can clog the pavement. The same requirements apply for the bedding layer aggregates, which must hold the entire pavement and traffic loads.

The hardness of the joint filling material therefore plays a decisive role. This is the central problem of the joint filling material. Hard materials such as granite or basalt usually demonstrate no pollutant retention, while pollutant reactive materials such as limestone or zeolites are too soft. The solution to this problem was therefore to develop a mixture of highly reactive adsorbent materials with a hard material such as granite. However, the potential pollution adsorbing agents such as natural or artificial zeolites also need to be analysed to assess their pollutant absorption capacity and crushing strength.

3. Maintenance

To ensure that the infiltration capacity of permeable pavements remains sufficient they generally need to be cleaned periodically. The maintenance intervals depend on a number of factors including pavement type, location, environmental conditions and traffic volumes. However, they typically require cleaning at least once every 10 years [17]. For PICPs, the uppermost part of the joint needs to be rinsed or vacuumed with special equipment. The joints then have to be refilled with a suitable material. The use of a combined rinsing/suction method is recommended and there are several different commercial systems available on the market (Fig. 4).

The cleaning requirements for permeable pavements subject to DIBt approval [24] are now described. The average infiltration capacity of the PICP surfaces must at least 97 mm/h. The average infiltration capacity of the PICP must be measured at least once every five years to ensure that the infiltration rate is higher than 97 mm/h. If these measurements are not undertaken, the DIBt approvals are no longer valid. If surface infiltration measurements demonstrate that the average infiltration rate is below 97 mm/h the pavement surface shall be cleaned. Cleaning can be performed using trucks fitted with specialized high pressure cleaning and vacuuming systems. The sludge produced from pavement cleaning must be disposed of according to German Water and Waste regulations. After the cleaning process has been completed, the paving joints shall be refilled with the original joint filling material. Failure to refill the joints can result in serious pavement damage by vehicles.

Fig. 4. Cleaning Vehicle with High Pressure Nozzles and Vacuum System.

4. Methodology

In order to determine the most effective combination of materials to use for the joint filling and bedding layer materials, six different experimental structures (Table 1) were investigated in the laboratory. The hydraulic behaviour of the six structures was tested in addition to their performance in removing total suspended solids, heavy metals and oil from stormwater. The six structures were evaluated during the laboratory tests to determine which of the six combinations was the optimal deign mix. A prototype scale installation using the optimal structure was then tested in the field.

Table 1. Six Different Permeable Structures for the Tests.

	Structure 1*	**Structure 2**	**Structure 3**	**Structure 4**	**Structure 5**	**Structure 6**
Joints	Basalt (1-3 mm)	Zeolite (0-4 mm)	Zeolite (0-4 mm)	Mix** (0-4 mm)	Adsorber (0-4 mm)	Granite (0-4 mm)
Bedding	Basalt (2-5 mm)	Basalt (2-5 mm)	Basalt (0-5 mm)	Basalt (0-5 mm)	Basalt (0-5 mm)	Basalt (0-5 mm)

** No longer allowed under German Paving Regulations*
*** Mix of adsorber and granite*

4.1. Hydraulic tests

The preliminary laboratory investigations of the six different paving structures (Table 1) were performed in test columns with internal diameters of 100 mm. Synthetic rainfall was applied to the columns using a rainfall simulator analogous to the large test facility specified in the DIBt test methods [24]. Since the joints of the new PICP system were narrow, the hydraulic conductivity of the joint material needs to be correspondingly high.

4.2. Removal of heavy metals

As heavy metals are seen as the main pollutants in road runoff in Germany their retention in the pavement is of utmost importance. These pollutants can be produced from the abrasion of tires (zinc, cadmium), brakes (copper) and other elements in the road and car park area (zinc, lead, etc.). For the testing procedure recommended by the DIBt standard [24] permeable pavements are exposed to a synthetic runoff containing zinc and copper. These two metals also give information about the pollution general removal performance of other metals. Cadmium shows similar pollution removal behaviour to zinc in permeable pavement structures and lead shows similar pollution removal behaviour to copper [25]. The load that is applied in the tests is equivalent to ten years of pollutant under real conditions.

4.3. Investigation of the TSS removal

The removal of total suspended solids in the columns was tested according to the DIBt test method [24] with a quartz powder between 2 microns and 200 microns in size. The DIBt test method requires that the total suspended solids test material be retained within the pavement during the two hour test duration and display a removal rate of more than 92%. If the joint material is too coarse, the fine particles will not be retained sufficiently in the pavement structure. If the joint filling material is too fine, it may not provide the required hydraulic conductivity.

4.4. Field site infiltration measurements

After the mixture of the granite with the synthetic adsorber in the joints (Structure 4) was identified as best solution for the joint filler, three different test fields were installed in Germany and the Netherlands in September/October 2011. One test field is located in Coesfeld (car park), one in Münster at a University car park (with five different pavement types) and one carpark in Dronten in the Netherlands. All sites were constructed with the new mixed joint material, on a (0 to 5 mm) basalt bedding layer, above a (0 to 45 mm) gravel sub-base between 350 and 450 mm thick (Fig. 5). The maximum width of the joints used for all installations was 5 mm. All test locations were continually used by vehicles over the test period from 2011 to 2014. No maintenance was performed on any of the field test pavements.

In order to measure the permeability of the field test areas, the German drip infiltrometer was used. According to the German paving regulations, PICPs must demonstrate an average infiltration capacity of at least 97 mm/h. Due to air-filled pores in the sub-base that may reduce the flowrate, an infiltration rate of 194 mm/h is required for new pavement installations [22]. The first surface infiltration measurements were undertaken in September 2011 directly following the pavement installation. The infiltration rates of the field installations were generally measured every three months. The infiltration results for three of the pavement types at the Münster field installation are presented in this paper. The three pavers included two new impermeable PICPs with different block sixes and one porous PICP for comparison purposes. Table 2 details the dimensions of the three pavers tested.

Fig. 5. Construction of the Coesfeld field Test Site.

Table 2. Three Paver Types Tested at Münster Field Installation.

	New PICP (1)	New PICP (2)	New Porous PICP
Joint Width (mm)	5	5	4
Paver Dimensions L/W/H (mm)	200/100/80	200/200/80	200/100/80

5. Results and Discussion

5.1. Hydraulic test results

The results of the hydraulic conductivity measurements are shown in Fig. 6. Structures 1 and 2 clearly demonstrated the highest infiltration rates (approximately 1,800 mm/h). This was probably due to the coarse (2-5 mm) bedding aggregate and the lack of aggregate sizes less than 2 mm. The infiltration results of Structures 3 to 6 using the new 0-5 mm basalt bedding layer specified by the new German standard are significantly lower (between approximately 800 and 1,200 mm/h).

The German requirements of 194 mm/h for a new PICP and 97 mm/h for older PICPs are indicated respectively by the two blue horizontal lines on Fig. 6. As can be seen, the tested infiltration rates easily achieve these targets. However, in the authors' opinion, the infiltration rates required by the German regulations are insufficient due to clogging processes and we recommend that an infiltration rate of over three times these values, i.e. at least 600 mm/h (red line in Fig. 6) be adopted for new PICPs. All structures tested in this study demonstrated infiltration rates in excess of this value so all the structures tests appeared suitable from a hydraulic point of view.

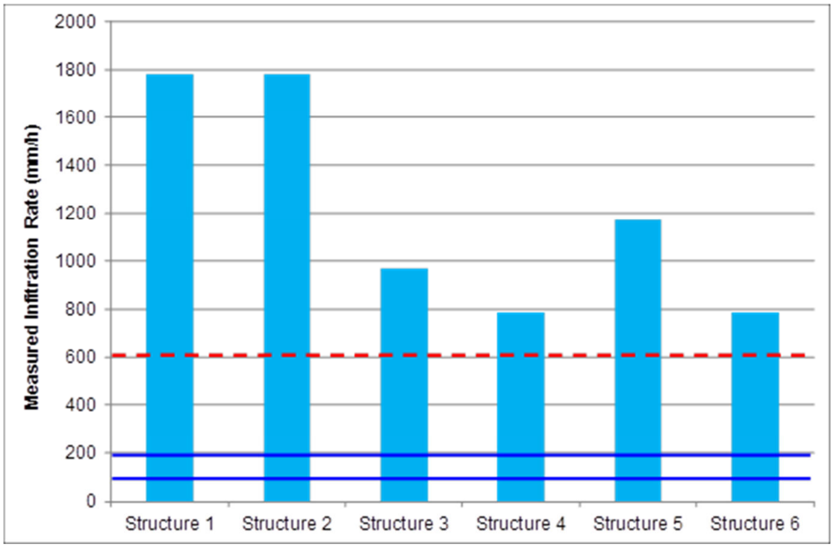


Fig. 6. Measured Infiltration Rates for Test Structures.

5.2. Heavy metal results

Figure 7 shows the results for the zinc removal tests. The differences between the joint materials are very clear. Structures 1 demonstrated the lowest zinc removal performance which was expected due to the using only basalt for the joints and bedding layer. Structures 2 and 3 also showed low zinc removal performance despite having Zeolite in the joints. This was possibly due to a reduced contact time between the zeolite and stormwater because of the high hydraulic conductivity caused by the 2 to 5mm basalt bedding layer. Structure 4 with the mix of zeolite and basalt in the joints had the best zinc removal performance. This structure was chosen for the field test installations. Structure 5 demonstrated the second highest zinc removal rate but this material is expensive and it has a low aggregate crushing strength. Structure 6 had a reasonable zinc removal performance but it has a low infiltration rate and was therefore deemed unsuitable. Copper test results were similar to zinc.

5.3. Investigation of the total suspended solids removal

Structures 2 to 6 were found to satisfactorily remove more than 92% of the total suspended solids from the synthetic stormwater. However, Structure 1 failed this test due to the high hydraulic conductivity of the materials.

5.4. Field site infiltration measurement results

Figure 8 shows the infiltration rate measurements at the Münster field site from November 2011 to November 2012. The measured infiltration rates were between 313 and >580 mm/h for all pavements tested which was sufficiently high according to the German regulations. The infiltration testing equipment was unable to measure rates higher than 580 mm/h so an asterisk on Fig. 8 denotes rates were greater than 580 mm/h. The porous pavement demonstrated a significantly higher infiltration capacity (>580 mm/h) in all tests because of the porous concrete blocks.

All three field installation test sites showed similar results to those in Fig. 8. The results suggest that the new bedding and joint structure performs well during the first years of operation and should continue to do so for many years to come. Monitoring of the infiltration rates of the three field installations will continue over the next five years.

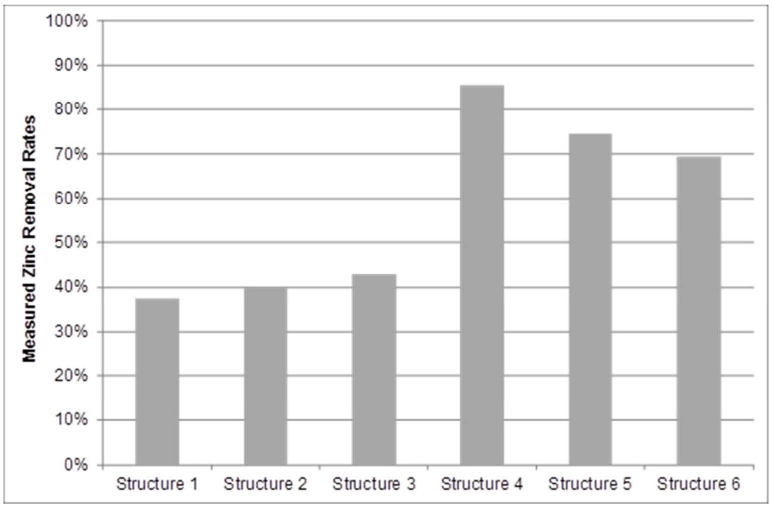


Fig. 7. Measured Zinc Removal Rates.

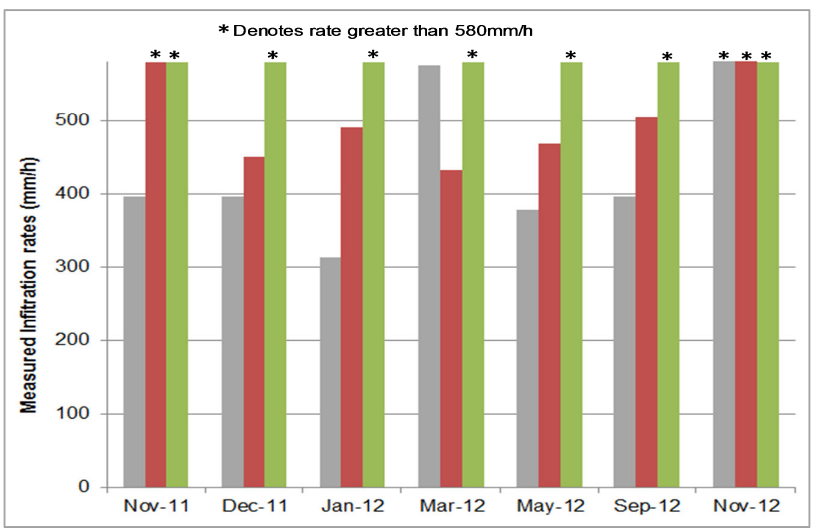


Fig. 8. Measured Infiltration Rates for Münster Field Installation.

5.5. Summary

In the past, a hard split rock (2 to 5 mm in diameter) was often used for the bedding layer of PICPs. However, new German paving guidelines have been introduced that specify the type of materials allowed to fill the joints of PICPs. For example, PICP bedding materials without fines may no longer be used. The introduction of the new guidelines necessitated new materials and PICP designs to be tested. In order to determine the most effective combination of materials to use for the joint filling and bedding layer materials, this study investigated six different experimental structures (Table 1) in the laboratory for hydraulic conductivity, Zinc and total suspended solids removal.

The hydraulic test results demonstrated that the infiltration rates for all structures tested were in excess of the minimum required value of 194 mm/h. These results suggest that all structures tested were suitable from a hydraulic point of view. The joint filling material mixture with a mix of zeolite and basalt (Structure 4) demonstrated the best zinc removal performance. Structures 2 to 6 were found to satisfactorily remove more than 92% of the total suspended solids from the synthetic stormwater. However, Structure 1 failed this test due to the high hydraulic conductivity of the materials.

A new type of two layer PICP paver was field tested with a 10 mm thick impermeable top layer and a 70 mm thick porous base layer. The new paver design allows water to percolate through paver and not just through the joint filling materials. The field testing results showed that the infiltration rate of the new paver easily exceeds the requirements of the new German guidelines. The new PICP paving stones can also be fabricated in any number of shapes, designs and textures and it is hoped that this will make PICPs a more attractive stormwater management systems for landscape architects and designers.

6. Conclusions

PICPs play an important role in the German stormwater pollution mitigation strategies, as the function of PICPs more closely replicates the natural hydrological cycle than other technical SUDS. PICPs must demonstrate a sufficiently high infiltration capacity to allow the required volumes of stormwater runoff to infiltrate into the ground and water table. To protect groundwater and receiving waters from stormwater pollutants PICPs must also have a high pollutant removal capacity. As such, German PICP systems require official general technical approval.

PICPs have suffered damage due to severe climatic conditions over the last few decades in Germany and new regulations have now been introduced to minimise future damage. The new regulations stipulate that PICPs with porous top surfaces may no longer be used and stormwater must now be infiltrated through the joints between PICP pavers. In addition, new German guidelines have been introduced that specify the type of materials allowed to fill the joints of PICPs. In order to determine the most effective combination of materials to use for the joint filling and bedding layer materials, this study investigated six different experimental structures in the laboratory for hydraulic conductivity, Zinc and TSS removal. The study found that:

- The hydraulic testing results showed that the infiltration capacity of all six structures tested were in excess of the minimum required value of 194 mm/h by the German paving regulations;
- The joint filling material mixture with a mix of zeolite and basalt (Structure 4) demonstrated the best zinc removal performance;
- Structures 2 to 6 were found to satisfactorily remove more than 92% of the TSS from the synthetic stormwater. However, Structure 1 failed this test due to the high hydraulic conductivity of the materials.

The infiltration capacity of new type of two layer PICP paver was field tested over a period of one year after installation. The results showed that the infiltration rates for the new PICP were considerably in excess of the requirements of the new German guidelines. It is anticipated that the new paver will demonstrate high infiltration capacity for many years.

The new PICP paving stones developed as part of this study were found to fulfil all criteria required to satisfy the new German General Technical Approvals protocol, as well as fulfil all German Building Standards. The new pavers can also be fabricated in any number of shapes, designs and textures and it is hoped that this will make PICPs a more attractive stormwater management option for engineers, landscape architects and designers in future.

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