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Article

Evaluating the Infiltration Performance of Eight Dutch Permeable Pavements Using a New Full-Scale Infiltration Testing Method

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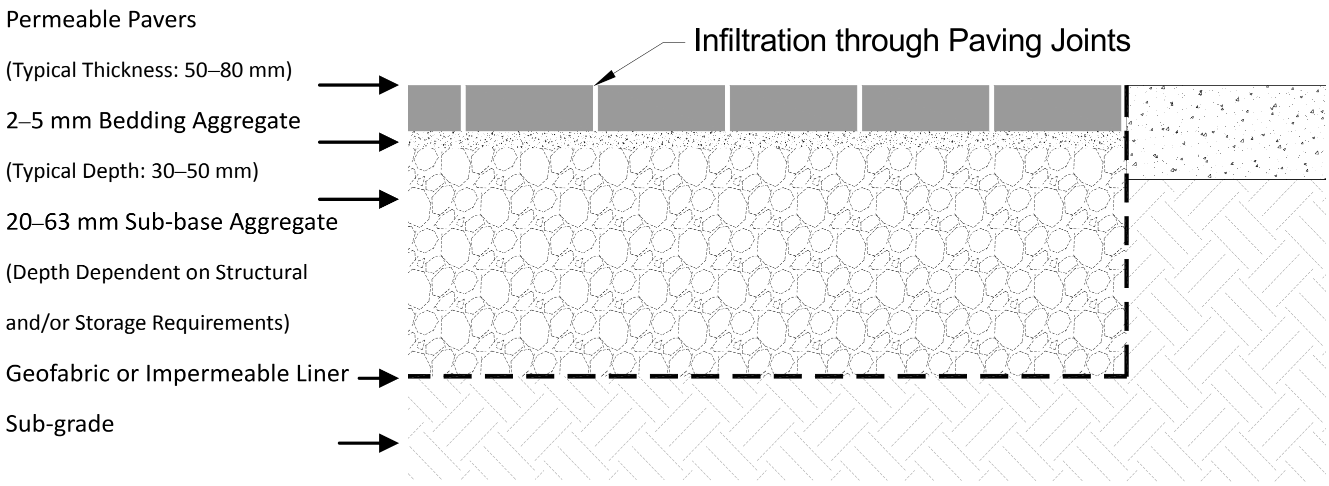
Abstract: Permeable pavements are a type of sustainable urban drainage system (SUDS) technique that are used around the world to infiltrate and treat urban stormwater runoff and to minimize runoff volumes. Urban stormwater runoff contains significant concentrations of suspended sediments that can cause clogging and reduce the infiltration capacity and effectiveness of permeable pavements. It is important for stormwater managers to be able to determine when the level of clogging has reached an unacceptable level, so that they can schedule maintenance or replacement activities as required. Newly-installed permeable pavements in the Netherlands must demonstrate a minimum infiltration capacity of 194 mm/h (540 l/s/ha). Other commonly used permeable pavement guidelines in the Netherlands recommend that maintenance is undertaken on permeable pavements when the infiltration falls below 0.50 m/d (20.8 mm/h). This study used a newly-developed, full-scale infiltration test procedure to evaluate the infiltration performance of eight permeable pavements in five municipalities that had been in service for over seven years in the Netherlands. The determined infiltration capacities vary between 29 and 342 mm/h. Two of the eight pavements show an infiltration capacity higher than 194 mm/h, and all infiltration capacities are higher than 20.8 mm/h. According to the guidelines, this suggests that none of the pavements tested in this study would require immediate maintenance.

Keywords: permeable pavements; infiltration rate; clogging; SUDS; full-scale test method

1. Introduction

Permeable (or porous) pavements are a type of sustainable urban drainage system (SUDS) technique that are used around the world to infiltrate and treat stormwater runoff. Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and basecourses, where it is filtered through the various layers (Figure 1). This can significantly reduce runoff volumes and discharge rates from paved surfaces [1–5] which can potentially minimise the risk of downstream flooding. Permeable pavements also provide considerable water quality improvements by treating and trapping stormwater pollutants [1,6–8].

Figure 1. Typical permeable pavement structure.



There are several types of permeable pavements typically used in Europe, including concrete pavers with wide joints or apertures (Figure 2a) and porous concrete pavers, either with or without wide joints (Figure 2b). These are usually manufactured as blocks and are generally referred to as permeable concrete interlocking pavers (PCIP). Concrete and plastic grid pavers (CGP and PGP) are also often used in Europe. The design and function of CGPs and PGPs are similar to PCIP; however, the areas of the individual pavers are generally much larger than those used for PCIP systems. They also have more open void spaces to promote infiltration. Stormwater is able to infiltrate through the large gaps in these pavers, which are usually filled with gravel, or topsoil planted with grass (Figure 2c).

Research has shown that urban stormwater runoff can contain significant concentrations of suspended sediments and gross pollutants [1,7,9]. Clogging is a result of fine, organic matter and traffic-caused abraded particles, blocking the gaps and surfaces of permeable pavement systems, due to physical, biological and chemical processes [8]. This clogging decreases the porosity/permeability of the paving surface and, hence, the infiltration rate of a system [9–11].

Figure 2. (**a**) Impermeable concrete PCIP (permeable concrete interlocking pavers); (**b**) porous concrete PCIPs; (**c**) grass-filled plastic grid pavers (PGPs).

It is important for stormwater managers to be able to determine when the level of clogging has reached an unacceptable level, so that they can schedule maintenance or replacement activities as required. In order to assess the reduction in infiltration capacity that occurs in permeable pavements over time due to clogging, a variety of infiltration test procedures have been utilised in the past. However, the results have generally been inconsistent and have shown a large variation in the range of infiltration rates measured [5,6,12–15]. As the number of global permeable pavement installations increases, a more reliable and more accurate method to measure surface infiltration rates is needed [16].

1.1. Infiltration Rate Testing

A number of previous permeable pavement infiltration studies [4,10,13,15] have been based on results using a modified version of either the single- or double-ring infiltrometer test (ASTM D3385-09) [17]. In these tests, rings are sealed to the pavement surface and filled with water. The time taken for the water to infiltrate through the permeable surface area is used to estimate an average infiltration rate (usually in mm/h) for the test location. Both the constant head and the falling head methods can be utilised in these testing procedures. Double-ring infiltrometer tests (DRIT) have generally been the preferred method in the past. This is because the outer ring is thought to reduce measurement errors and to prevent lateral flow from occurring beneath the rings. However, on pavements where the infiltration rate is so high that it is difficult to supply enough water to both rings, the single-ring surface infiltration test [4] has been used (Figure 3c).

Three variations of ring infiltrometers used in past permeable pavement studies are shown in Figure 3. Other permeable pavement infiltration research has been undertaken using specially fabricated rainfall simulation infiltrometers [6,9]. A new Standard Test Method for the Surface Infiltration Rate of Permeable Unit pavement Systems (ATSM C1781M-13) [18] has recently been published. However, to date, there have been no studies published using this method.

Figure 3. Modified ring infiltrometers used for permeable pavement testing: (**a**) double-ring infiltrometer tests (DRIT) [15]; (**b**) square, double-ring [13]; (**c**) single-ring surface inundation test [4].

The permeable pavement infiltration testing methods described above are based on the infiltration rate through a very small area of the pavement that is used to represent the total pavement area infiltration. For example, the area of the inner ring of the ASTM D3385-09 [17] DRIT test is 0.0707 m^2. The minimum area recommended by the Dutch guidelines [19] is even smaller, at only 0.01 m^2. Using such small areas for testing could potentially lead to erroneous results, as a number of studies have demonstrated a high degree of spatial variability between different infiltration measurements undertaken on the same pavement installation [4,9,13,20]. It was hypothesised that more accurate infiltration results may be produced by significantly increasing the area of the pavement surface being tested. By inundating a much larger area of pavement during testing, it was anticipated that any spatial variations in infiltration capacity would be averaged-out, and this would produce more reliable infiltration data.

In order to test this hypothesis, this study developed and trialled a new, full-scale infiltration testing method. Using the new method, it was possible to test the infiltration capacity of large sections of existing permeable pavements at one time. This paper describes the new experimental test procedure developed in the Netherlands to more accurately determine the surface infiltration rate of existing permeable pavement installations. The results from eight test locations in the Netherlands using the new infiltration testing method are presented and compared to national guideline requirements.

2. Methodology

In order to evaluate the performance of the new, full-scale infiltration testing method, the method was first trialled on an existing permeable pavement street installation that had been in service for over seven years in Utrecht in the Netherlands. The results of the initial testing were successful [21] and showed that the new method could be used to accurately measure infiltration rates of permeable pavements *in situ* after full-scale testing and tests with ring infiltrometers. The new testing method was therefore used on the eight existing pavements in five different municipalities evaluated in this study. The testing methodology for the eight test locations in the Netherlands is discussed in the following sections.

2.1. Test Area Selection

To enable an accurate estimation of the average surface infiltration rate using the new test method, a permeable pavement area of approximately 50 m^2 was recommended for all tests. This minimum area is recommended in order to obtain a good representation of the whole surface and to minimise any potential leakage problems. Roads in the Netherlands are typically five meters wide, which means the minimum length of the test pavements should ideally be at least 10 m (5 m × 10 m = 50 m^2). This area is over 700-times greater than the area of the inner ring used in typical infiltrometer tests. However, achieving this was dependent on site practicalities, such as pavement width, length, slope and cross-fall, the location of drainage gullies, parked cars and resident access requirements. It should be noted that in order to undertake the testing, it was necessary to close the section of pavement for a number of hours. It is therefore recommended that local council permission be obtained before any testing is conducted.

2.2. Water Containment

To accurately define the infiltration testing area and to contain the water used to infiltrate the pavement, it was necessary to construct small, temporary dams at the ends of the pavement test sections. The roadway kerb and gutter system retained the water on the sides of the pavement test sections. A number of dam variations were trialled at the eight different test locations (Figure 4). These included:

1. Soil core wrapped in plastic sheeting;
2. Sand core wrapped in geotextile;
3. Soil- or sand-filled plastic bags;
4. Impermeable barriers inserted into paving gaps; and
5. Use of existing traffic calming devices (speed-humps).

Figure 4. Various dam variations used at the different test locations; (**a**) impermeable barriers; (**b**) plastic wrapped soil core; (**c**) soil-filled plastic bags.

2.2.1 Recommendations

Where possible, one of the preferred methods of containing the water within the test site is to choose a section with an existing raised traffic calming device (speed hump) at one (or both) ends. This saves considerable setting-up time and also minimises leakage problems during testing. It is also advisable to select the section of pavement with the least number of existing drainage gullies within the pavement surface or gutter. Drainage gullies need to be properly sealed to prevent water from leaking from the test area and entering the underground stormwater drainage system. This can be both difficult to accomplish and time consuming. Of all the methods trialled to create temporary dams, the soil-filled were found to be the most effective. This was due to their ability to properly seal the test sections, the rapid filling and emptying characteristics of the bags, the ability to reuse the material and the ease of construction by hand without the need for heavy machinery.

2.3. Water Supply

The new infiltration test requires large volumes of water to be discharged onto the test paving section in order to inundate the pavement surface. Depending on the site location, a number of different water supply options were trialled in this study, including transporting water directly to the site with water trucks (Figure 5a) or water tanks (Figure 5b) and pumping water directly from nearby canals (Figure 5c).

Figure 5. (**a**) Water truck supply; (**b**) water tank supply; (**c**) pumping from canal.

After the pavement test area had been selected and sealed with temporary dams, the pavement area was inundated with water to the maximum allowable water level possible that would not cause overtopping of the roadway kerb and gutter system. The maximum inundation depth was dependent on the type of construction. However, this was generally between 50 and 90 mm from the lowest point in the pavement to the top of the gutter. Due to the different levels of the pavement surface, this meant that the depth of water in the inundated test section was dependent on the measurement location, with the lowest pavement elevation generally having the highest inundation water levels.

2.3.1 Recommendations

Of the three water supply methods trialled, it was found that pumping the water from a nearby canal was the easiest option, where this option was available. This method offered total flexibility with types of testing and also offered an unlimited availability of water. It is recommended to include a flowmeter in the water supply line to allow accurate monitoring of water inflow rates. Water trucks were the second easiest option. However, these had the disadvantages of being expensive and difficult to arrange, manoeuvre and park, and they generally had only limited water supply capacity. When a water truck must be used, it is advisable to ensure that the outlet is fitted with a flowmeter to measure flow rate into the test pavement area.

2.4. Determining Pavement Infiltration Rates

Pressure transducers were used in the study as the primary method of measuring and recording the reduction in water levels over time at various locations on the pavement surface. Two wireless, self-logging pressure transducers were installed at the lowest points on the left-hand and right-hand sides of each test pavement area (Figure 6a). The transducers continuously monitored the static water pressures at those locations and transmitted this information to a laptop computer. The static water pressure was then converted to an appropriate depth of water above the pavement. This process produced accurate and reliable data over the duration of the tests. It also enabled visual representation of the pavement infiltration process.

Three different measurement methods (Figure 6) were used in conjunction with the pressure transducers in order to calibrate and verify the transducer readings. The three methods were:

1. Hand measurements;
2. Calibrated underwater camera;
3. Time-lapse photography.

Figure 6. (**a**) Minidiver installed at lowest point of pavement; (**b**) hand measurement point; (**c**) underwater camera set-up; (**d**) underwater camera view.

These three methods are explained in more detail below.

2.4.1. Hand Measurements

Water level measurements were taken using a simple 300-mm hand ruler (Figure 6b) at strategic locations on the pavement surface throughout the duration of the testing. These measurements were used to verify the functionality and accuracy of the self-logging pressure transducers, as described above. Photographs of each hand measurement were also taken for documentation and verification purposes.

2.4.2. Calibrated Underwater Camera

A high-definition video camera was also used at a number of strategic locations to record the decrease in pavement water levels over the duration of the tests. The camera was placed inside a waterproof, calibrated, transparent box, so that it could capture the entire infiltration process (Figure 6c). This system allowed real-time monitoring of the entire infiltration process and also facilitated precise verification of the pressure transducer measurements.

2.4.3. Time-Lapse Photography

Time-lapse photography was used at each test location to record all research activities and to enable verification of the pressure transducer and hand measurements. The time-lapse photographs were also used to compile an accelerated video of the entire pavement testing.

2.4.4. Recommendations

While pressure transducers and loggers provide an abundance of data and allow informative and attractive graphs to be complied, much care needs to be taken to ensure that the pressure transducer readings are verified and accurate. Pressure transducers can be unreliable and inaccurate. They have also been shown to be sensitive to external influences, such as wind effects and changes in atmospheric pressures [21]. Therefore, the high frequency data from pressure transducers is useful for a detailed infiltration curve, but it is highly recommended that transducer readings are calibrated and verified using at least one of the other methods described above.

2.5. Study Test Locations

The infiltration rates of eight existing permeable pavements in the Netherlands were tested in the current study. The locations and details of the pavements are listed in Table 1. All test locations are located in residential areas (30 km/h zones). No maintenance other than street sweeping has taken place at the locations. All tests were carried out after an antecedent dry period of at least three days.

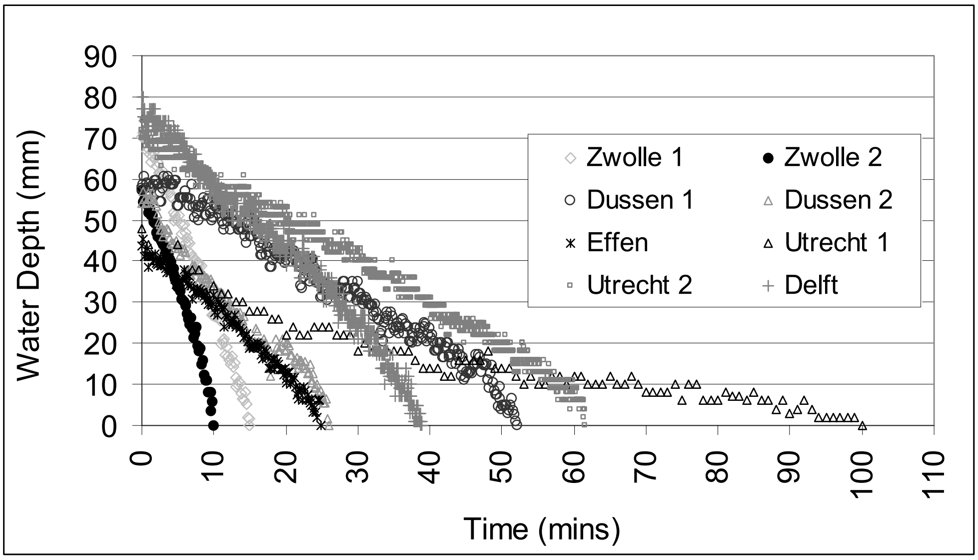
Table 1. Permeable pavement locations tested in the Netherlands.

Test location	Street name	Type of pavement	Year of construction	Test area (m^2)	Test date
Zwolle 1	Pieterzeemanlaan	Porous Concrete PCIP	2006	44.2	11/15/2013
Zwolle 2	Pieterzeemanlaan	Porous Concrete PCIP	2006	39.9	11/15/2013
Dussen 1	Groot Zuideveld	Impermeable Concrete PCIP	2006	59.5	10/23/2013
Dussen 2	Groot Zuideveld	Impermeable Concrete PCIP	2006	69.7	10/23/2013
Effen 1	Baanakker	Impermeable Concrete PCIP	2006	29.4	10/30/2013
Utrecht 1	Nijeveldsingel	Impermeable Concrete PCIP	2006	51.9	11/28/2012
Utrecht 2	Brasemstraat	Impermeable Concrete PCIP	2006	60.0	06/13/2013
Delft 1	Drukkerijlaan	Impermeable Concrete PCIP	2005	74.0	06/19/2013

2.6. Calculating Infiltration Rates

All eight test pavements (Table 1) were sealed, inundated and monitored as described above. The pressure transducer readings were then plotted against time to generate precise infiltration curves for each of the test sites (Figure 7). Simple linear regression analysis was used to generate lines of best fit for the transducer readings from each site. The equations of the linear regression lines were then used to calculate the average infiltration rate in mm/h for each test site (Table 1).

Figure 7. Infiltration curve results for the eight permeable pavements tested in the study.



3. Results

The surface infiltration rates recorded for each of eight test pavements using the new experimental test procedure are shown in Figure 7.

The linear regression analysis results for the eight test pavement measurements are listed in Table 2.

Table 2. Linear regression analysis results for the eight test pavements.

Test location	R^2	Equation	Max water level (mm)	Total time (mins)	Calculated infiltration (mm/h)	Percentage of recommended EU value (194 mm/h)
Zwolle 3	0.9844	y = −5.211x + 58.935	57	10	342	176%
Zwolle 1	0.9928	y = −4.634x + 73.373	71	15	284	146%
Dussen 2	0.9624	y = −1.8498x + 52.742	57	26	132	68%
Delft 1	0.9821	y = −1.8195x + 77.848	80	39	124	64%
Effen 1	0.9837	y = −1.6099x + 44.451	45	25	109	56%
Utrecht 2	0.9792	y = −1,031x + 70.576	72	61	71	36%
Dussen 1	0.979	y = −1.0572x + 61.858	60	52	69	35%
Utrecht 1	0.8826	y = −0.3577x + 34.154	48	100	29	15%

4. Discussion

Although the eight permeable pavements tested in this study were of a similar construction type and of similar age, Table 2 shows a large variation in the calculated infiltration rates between the eight study pavements. This variation in results is similar to the findings of a number of previous studies that have attempted to quantify the infiltration rates of permeable pavements [4,13,16,21–23]. The infiltration rates of the eight test pavements differed from between 29 and 342 mm/h.

There are a number of potential reasons for the observed variations in the surface infiltration rates between the test pavements, including:

- Age: although most of the pavements were generally of a similar age range, it would be reasonable to expect small variations in surface infiltration capacity in the older pavements.
- Construction: While the construction of the test pavements were generally similar to that shown in Figure 1, there were slight differences between the sites. These included the size of the paving joints, different types of bedding aggregates and different pavement laying processes.
- Maintenance: There were distinct variations in the pavement maintenance procedures between the different municipalities. Some municipalities conducted occasional street sweeping of their permeable pavements. However, as this was done to all pavements, this is generally not considered as targeted maintenance to improve the permeable pavement performance and to reduce clogging.
- Variations in hydraulic ground conditions: The water table was higher at some pavement test locations (particularly in the western areas of the Netherlands), while the permeability of soils in the eastern test locations were generally higher.
- Environmental site conditions: The type and amount of trees surrounding the pavements were not the same. Trees are known to affect the infiltration rate of permeable pavements [15]. Other test pavement locations may have been affected by the close proximity of industrial areas.
- Pavement usage: There were distinct variations observed between the type and number of vehicles using the different pavements on a daily basis.

4.1. Dutch Permeable Pavement Infiltration Guidelines

Guidelines for the construction and performance of permeable pavements are generally limited in the Netherlands. However, guidelines on acceptable infiltration rates for newly-installed permeable concrete pavement systems in the Netherlands have been developed by Kiwa Nederland [19] in 2014, and local government engineers and designers often refer to these guidelines when designing new permeable pavement systems. Recently published Kiwa permeable pavement infiltration testing guidelines [19] stipulate the following:

> "A minimum of three infiltration tests shall be performed. If all three tests demonstrate an average infiltration rate of equal to or greater than 194 mm/h (540 L/s/ha), the pavement is deemed to comply."

A number of other European countries also have construction and infiltration guidelines for concrete permeable pavements. Newly-installed permeable pavements systems in the Netherlands, Belgium and Germany all need to demonstrate an infiltration capacity of 194 mm/h [24–26]. Every test should demonstrate a minimum infiltration rate of 97 mm/h.

The overall infiltration rates calculated for six of the eight pavements tested in this study were below the Kiwa recommendation of 194 mm/h (Table 2). Other permeable pavement guidelines in the Netherlands [27] recommend that maintenance is undertaken on permeable pavements when the infiltration falls below 0.5 m/d (20.8 mm/h). According to these guideline values, none of the pavements in Table 2 would require immediate maintenance. Previous studies have demonstrated that infiltration rates that have diminished over time due to clogging can be restored by undertaking pavement maintenance, such as street sweeping and vacuum cleaning [4,6,28].

An interesting outcome from the study was the differences in perceptions between the various maintenance personnel regarding the measured infiltration rates of the test pavements within their municipalities. Interviews were conducted with a variety of maintenance personnel from the different municipalities where the full-scale tests were performed in order to ascertain their opinions on the infiltration performance of the pavements. For example, some of the people interviewed were satisfied with a low infiltration rate just above the 20.8 mm/h corresponding to the RIONED [27] recommendations. However, others were disappointed with the relatively high infiltration rate, as it was just above the KIWA [19] guideline of 194 mm/h, and they expressed concern that this value would reduce over time.

Infiltration rates of newly-installed permeable pavement systems have been shown to be very high. However, this has been shown to decrease significantly over time [9,12,13,23], and it is the long-term infiltration performance of a pavement that determines their ultimate success or failure [11]. Whether the surface infiltration rate obtained from testing is considered acceptable or not depends on a number of factors, including the location of the pavement, the intended purpose of the pavement and the stakeholder expectations. Most stakeholders in the Netherlands expect a life span of 20 to 60 years, comparable with the life span of conventional stormwater drainage infrastructure. Most roads in the Netherlands will be reconstructed within 20 years. From this data, it should be considered to test the pavement right after construction and every five years. Our suggestion is that municipalities should plan to undertake maintenance after about 10 years of continuous use.

5. Conclusions

This study used a newly-developed, full-scale infiltration test to evaluate the infiltration performance of eight permeable pavements in five municipalities that had been in service for over seven years in the Netherlands. Traditional permeable pavement infiltration testing methods generally base results on the infiltration rates obtained through a very small area of the pavement, which is then used to represent the total pavement area infiltration. This approach of using small areas for testing could potentially lead to erroneous results being obtained. This study tested the hypothesis that more accurate infiltration results may be produced by significantly increasing the area of the pavement surface being tested. An earlier study on one location in Holland demonstrated that the newly-developed, full-scale infiltration testing methodology was successful and produced reliable surface infiltration results [21]. Issues that need to be considered when using the new test method are also presented in the paper.

Infiltration rates of newly-installed permeable pavement systems are generally very high, although they have been shown to decrease significantly over time. Newly-installed permeable pavements in the Netherlands must demonstrate a minimum infiltration capacity of 194 mm/h. This study found that only two of the measured infiltration results of the eight tested pavements were above the 194 mm/h requirement. Other permeable pavement guidelines in the Netherlands recommend that maintenance should be undertaken on permeable pavements when the surface infiltration falls below 20.8 mm/h. According to these guideline values, none of the eight pavements tested in this study would require immediate maintenance.

While the results of the study may initially appear discouraging at first, the study found that whether the results were considered acceptable or not depended on a number of factors. These included the location of the pavement, the intended purpose of the pavement and the stakeholder expectations and perceptions. The authors advise testing the pavement right after construction and again after five years to estimate the clogging rate of the pavement. Municipalities should plan to undertake maintenance around 10 years of continuous use. The findings of this study will help planning the required maintenance of the pavements with more confidence so that they will continue to perform over their intended design life.

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Author Contributions

This study was undertaken as a collaborative research project by the Delft University of Technology, the University of the Sunshine Coast in Australia, Hanze University of Applied Sciences and by TAUW in the Netherlands. The experimental design of the project was undertaken by Floris Boogaard, Terry Lucke, Frans van de Ven and Nick van de Giesen. The majority of the experimental field work was conducted by Floris Boogaard with assistance from Terry Lucke. The paper was written by all four authors equally.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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