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Evaluation of a new experimental test procedure to more accurately determine the surface infiltration rate of permeable pavement systems

Terry Lucke^{a*}, Floris Boogaard^{b,c} and Frans van de Ven^c

^a*School of Science and Engineering, University of the Sunshine Coast, Sippy Downs, QLD 4558, Australia;* ^b*Tauw BV, BU Ruimtelijke Kwaliteit, Zekeringstraat 43g, PO Box 20748, 1001 NS Amsterdam, the Netherlands;* ^c*Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2600 AA Delft, the Netherlands*

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Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving surface in order to reduce run-off volumes and to improve water quality by removing sediment and other pollutants. However, research has shown that permeable pavements can become clogged over time and this reduces their infiltration capacity. In order to assess the infiltration of permeable pavements, 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. This paper evaluates the performance of two new experimental test methods developed in the Netherlands to more accurately determine the surface infiltration rate of existing permeable pavement installations. The two methods were the falling head full-scale method and the constant head full-scale 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. Double ring infiltrometer tests were also performed to enable a comparison of the results. The study found that the new falling head full-scale testing method produced the most accurate results.

Keywords: permeable pavement; infiltration rate; clogging; sustainable urban drainage systems

Introduction

Paving types

Permeable (or porous) pavements have been in commercial use now for around three decades globally. They are generally implemented as part of an overall water management strategy such as Sustainable Urban Drainage Systems (SUDS) in Europe, Water Sensitive Urban Design (WSUD) in Australia, or Low Impact Development (LID) in the USA. Permeable pavements have considerably different design objectives and requirements from those for conventional pavements. However, they are often used as an alternative to conventional hard impervious surfaces, such as roads, car parks, foot-paths and pedestrian areas. Their use can result in numerous stormwater management and environmental benefits.

*Corresponding author. Email: tlucke@usc.edu.au

Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and base courses where it is filtered through the various layers. This can significantly reduce run-off volumes and discharge rates from paved surfaces (Bean, Hunt, & Bidelspach, 2007; Collins, Hunt, & Hathaway, 2008; Fletcher, Duncan, Poelsma, & Lloyd, 2005; Hunt, Stevens, & Mayes, 2002; Pratt, Mantle, & Schofield, 1995) which can potentially minimise the risk of downstream flooding. Permeable pavements also provide considerable water quality improvements by treating and trapping stormwater pollutants (Brattebo & Booth, 2003; Dierkes, Kuhlmann, Kandasamy, & Angelis, 2002; Pratt, Mantle, & Schofield, 1989; Siriwardene, Deletic, & Fletcher, 2007).

Permeable pavements come in several forms, and are either monolithic or modular (Fletcher et al., 2005). Monolithic structures include porous asphalt and porous concrete that allow infiltration through the pavement surface only. Porous asphalt is similar to typical hot mix asphalt but the fine portion of the aggregate is omitted. Likewise, most of the fine aggregates normally included in the production of traditional concrete are omitted during the production of porous concrete.

Modular structures include concrete block pavers with open joints or apertures (Figure 1) to allow infiltration through the surface joints. A number of manufacturers produce porous concrete block pavers which allow water to infiltrate through the paving surface as well as through the joints. Concrete paving blocks are generally referred to as permeable interlocking concrete pavers (PICPs).

The joints or spaces between PICPs are not filled with sand as they are with conventional pavers. Instead, the open spaces between the pavers are usually filled with the same 2 to 5 mm aggregate that is used for the paving bedding layer. Filling the joints with bedding aggregate promotes rapid infiltration between the pavers. A typical PICP paving bed cross-section is shown in Figure 2.

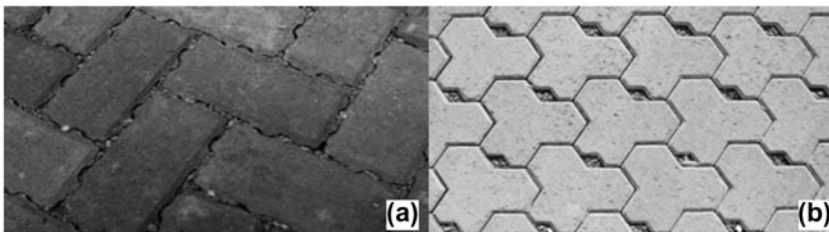


Figure 1. PICPs with wide joints (a) and apertures (b).

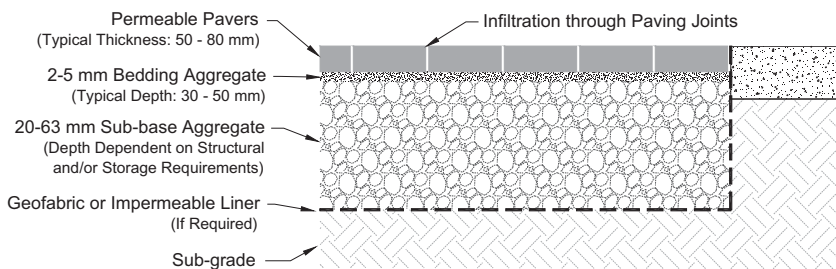


Figure 2. Typical PICP structure.

Infiltration and clogging

Infiltration rates of newly installed permeable pavement systems have been shown to be extremely high. However, it is the long-term infiltration performance of a pavement that determines its ultimate success or failure (Yong & Deletic, 2012). While there is a substantial amount of literature on the infiltration capacity of newer installations, the number of research studies undertaken in relation to permeable pavements that have been in operation for several years has been limited (Borgwardt, 2006; Lucke & Beecham, 2011; Pezzaniti, Beecham, & Kandasamy, 2009).

Previous research has established that urban stormwater run-off contains significant concentrations of suspended sediments and a variety of pollutants. These include: heavy metals, total phosphorous (TP), total nitrogen (TN), oils, and other hydrocarbons (Boogaard, Blanksby, de Jong, & van de Ven, 2010; Dierkes et al., 2002; Duncan, 1999; Sansalone, Koran, Smithson, & Buchberger, 1998; Sartor, Boyd, & Agardy, 1974). There is therefore some concern amongst designers of these systems that permeable pavements used as pollutant source control devices will tend to clog quickly, and that this could result in a significant loss of infiltration capacity. This has resulted in an increasing number of research studies into the clogging processes that take place in permeable pavements (Brattebo & Booth, 2003; Lucke & Beecham, 2011; Pezzaniti et al., 2009; Pratt et al., 1995; Yong & Deletic, 2012).

Owing to the design of permeable pavements, some degree of clogging will be inevitable (Yong & Deletic, 2012) and further research is required before any reliable predictions can be made on the practical lifespan of these systems. A number of studies have shown that even visually ‘clogged’ systems can still demonstrate satisfactory infiltration rates through the pavement surface (Li, Kayhanian, & Harvey, 2013; Lucke & Beecham, 2011). Whether the infiltration rate is considered acceptable or not depends on a number of factors, including the location of the pavement. For example, in the Netherlands, and much of Europe, newly installed permeable pavements must demonstrate a minimum infiltration capacity of 270 l/s/ha, or 97.2 mm/h (Forschungsgesellschaft für Straßen- und Verkehrswesen [FGSV], 1998; Opzoekingscentrum voor de Wegenbouw [OCW], 2008; Wohlfahrt, 2012). While this infiltration rate may be considered acceptable in Europe, it may not be acceptable in countries with high intensity rainfall characteristics such as Australia or Brazil for example. Another important factor as to whether a permeable pavement is deemed to be functioning satisfactorily or not, is the method used to determine the infiltration rate.

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. As the number of permeable pavement installations increases, the need for a proper tool to measure their surface infiltration functionality, especially with respect to clogging, is also increasing (Li et al., 2013). This paper evaluates the performance of a new experimental test procedure developed in the Netherlands to attempt to more accurately determine the surface infiltration rate of existing permeable pavement installations.

Background

Previous infiltration testing studies

Currently, there is no single standard method for measuring the surface permeability of this type of pavement and multiple methods have been employed in existing studies for

measurement of surface permeability of porous asphalt and pervious concrete materials and pavements (Li et al., 2013). A number of studies have used surface infiltration testing to quantify the hydrologic performance of permeable pavement systems. This is generally undertaken by measuring the infiltration rate of water through a particular section of the pavement surface. While a variety of infiltration test procedures have been used, most are based on some type of modified single or double ring infiltrometer test.

Ring infiltrometer tests were originally developed to determine the hydraulic conductivity of in situ field soils for evaluation of their irrigation properties and for other related media drainage performance-testing purposes. Double ring tests are generally the preferred and more accurate method, as the outer ring helps reduce errors caused by potential lateral flow through the media under the rings. However, single ring infiltrometers are often used when the hydraulic conductivity of the media is very high as it can be difficult to keep water supplied to two rings in these conditions. The rings are driven into the media and water is supplied to the rings using either a constant head or a falling head method.

Constant head means that the water level inside the rings is kept at a constant, predetermined level for the duration of the testing. This is achieved by supplying water to the rings at a rate equal to the infiltration rate. The flowrate of the water (in l/s) is then divided by the cross-sectional area of the ring to calculate the infiltration rate (usually reported in mm/h/m², or simply mm/h). In the falling head method, a relatively large volume of water is supplied to the rings at one time and the time taken for the water to fall between two predetermined points inside the rings is measured. The average flowrate is calculated by dividing the total volume of water contained between the two points within the ring by the time taken for the water to fall. The infiltration rate is then calculated in a similar way to the constant head method.

Numerous studies have used some type of modified version of the media ring infiltrometer tests to estimate the infiltration capacity of permeable pavements (Bean et al., 2007; Fassman & Blackburn, 2010; Lucke & Beecham, 2011). The main challenge with using ring infiltrometer tests on permeable pavements is that the test rings are not able to penetrate the concrete test surface to seal against leakage, as they are in soil infiltration tests (Bean et al., 2007). Therefore, the rings need to be sealed against the pavement surface using some type of waterproof sealant or adhesive (Figure 3). This approach has been found to produce satisfactory results in most studies of this type.

Owing to the difficulty of supplying water at a constant flowrate in the field, the falling head method is more commonly used to estimate the infiltration rate through permeable pavement surfaces. As with media hydraulic conductivity testing, the single ring infiltrometer test is also often used on pavements with infiltration rates that are too high to maintain a hydraulic head, or to fill both rings with sufficient water at the same time. This variation of the single ring falling head method is also known as the surface inundation test (Bean, Hunt, Bidelsbach, & Burak, 2004). A number of studies have also trialled other infiltrometer ring sizes and shapes in order to try to achieve more accurate infiltration results (Beecham, Pezzaniti, Myers, Shackel, & Pearson, 2009; Gerrits & James, 2002; Lucke & Beecham, 2011).

A number of variations to the ring infiltrometer tests described above have been developed in the USA and these are often used to test the permeability of permeable pavements in American studies. The two main infiltration tests used on pavements in the USA are the ASTM C1701 and NCAT permeameter methods. The ASTM C1701 test method was developed under the jurisdiction of ASTM Technical Committee and uses the constant head principle (Li et al., 2013). The NCAT permeameter was

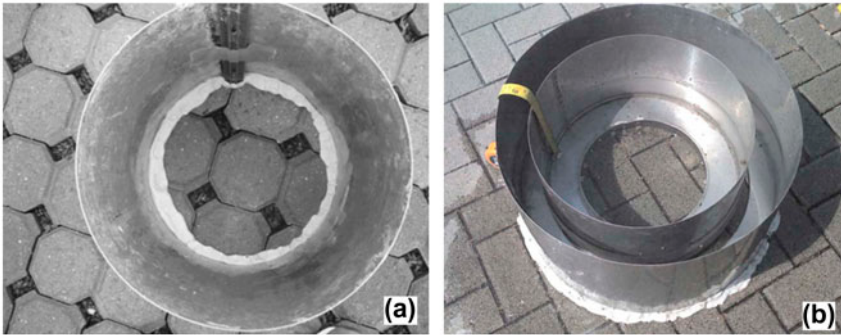


Figure 3. Modified ring infiltrometers for permeable pavement testing with waterproof sealant (a) single ring (Bean et al., 2007); (b) double ring (Fassman & Blackburn, 2010 – reproduced with permission).

developed by the National Center for Asphalt Technology (NCAT) in the late 1990s and uses the falling head principle. Li et al. (2013) undertook a comparison of these two methods and they found that both methods can be used effectively to measure the permeability of all pavement surface types (Figure 4). However, they did find that the ASTM C1701 method produced more conservative results which were generally between 50% and 90% lower than those produced using the NCAT method.

All of the permeable pavement infiltration testing methods described above have increased knowledge of testing methods and produced valuable results. However, all the results that these methods produce are based on the infiltration rate through a very small area of the pavement that is used to represent the total pavement area infiltration. A number of studies have demonstrated a high degree of spatial variability between

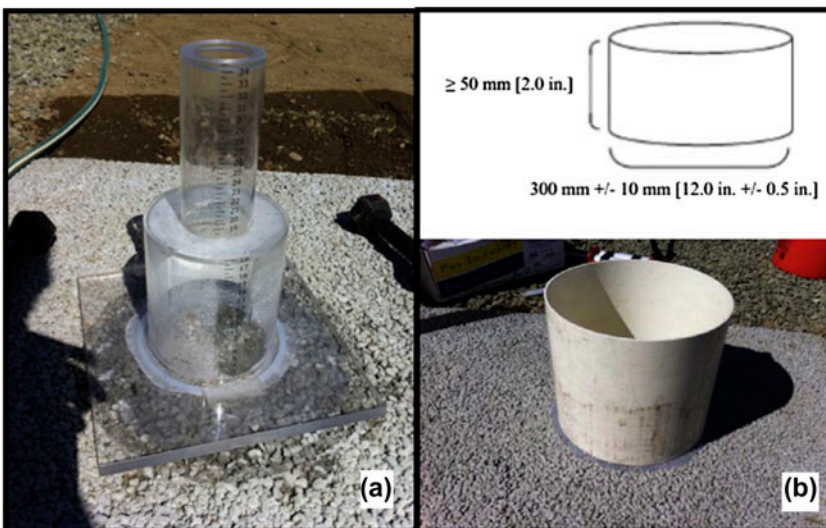


Figure 4. (a) NCAT permeameter; and (b) ASTM C1701 test method used by Li et al. (2013 – reproduced with permission).

different infiltration measurements performed on the same pavement installation (Bean et al., 2007; Borgwardt, 2006; Lucke & Beecham, 2011; van Dam & van de Ven, 1984). For example, lower elevations of permeable pavements, and areas receiving direct run-off from impervious surfaces, generally demonstrate lower infiltration rates as a result of clogging caused by relatively higher sediment loading rates in these areas. Conversely, higher sections of permeable pavements often demonstrate higher infiltration rates as they are less prone to clogging. This inherent spatial variability in infiltration capacity may reduce the accuracy of these testing methods and could potentially produce highly unrealistic infiltration performance results if the wrong testing locations were chosen.

If a method of surface infiltration testing could be developed that measured the infiltration performance of whole sections of permeable pavements at the same time, this could hypothetically lead to a more accurate estimation of the actual infiltration capacity of existing permeable pavement installations. In order to test this hypothesis, this study developed and trialled a new full-scale infiltration testing method which was able to evaluate the infiltration capacity of large sections of existing permeable pavement installations simultaneously. This paper presents the initial study results from the new infiltration testing method.

Methodology

The new full-scale infiltration testing method was trialled on an existing permeable pavement street installation that had been in service for over seven years in Utrecht in the Netherlands. The structure of the pavement was similar to that shown in Figure 2 (80 mm pavers, 30 mm bedding aggregate and 200 mm sub-base aggregate). The permeable pavement area tested at one time was approximately 65 m² (13.0 m long × 5.0 m wide). In order to accurately define the infiltration testing area, and to contain the water used to infiltrate the pavement, a small temporary retaining dam was constructed at one end of the pavement test section. The water at the other end was contained by an existing raised traffic calming device (speed hump). Two existing drainage pits (inlets into the underground sewer network) within the test area were also sealed to prevent water from entering the underground stormwater drainage system.

Water was pumped into the test paving section from a nearby canal in order to inundate the pavement surface. It took approximately 25 minutes to inundate the surface and once this was completed, the time taken for the water to drain from the pavement was recorded. Two different testing methods were used in the study, namely, the falling head full-scale (FHFS) method, and the constant head full-scale (CHFS) method.

For the FHFS method, the test pavement area was inundated to the maximum allowable water level possible that would not cause overtopping of the roadway kerbing system. This maximum depth was 90 mm at the lowest point in the pavement. This is shown as LHS (left hand side) in Figure 5. The different levels of the pavement surface meant that the depth of water in the inundated pavement sections varied from a minimum depth of 7 mm in the centre of the roadway to a maximum depth of 90 mm. Once the maximum water level was reached for the FHFS test, the water supply was then turned off. The time taken for the permeable pavement surface to drain at the LHS and right hand side (RHS) locations (Figure 5) was measured and recorded. The FHFS infiltration rate was then calculated by dividing the maximum water levels recorded at LHS and RHS by the time taken to fully drain at these locations.

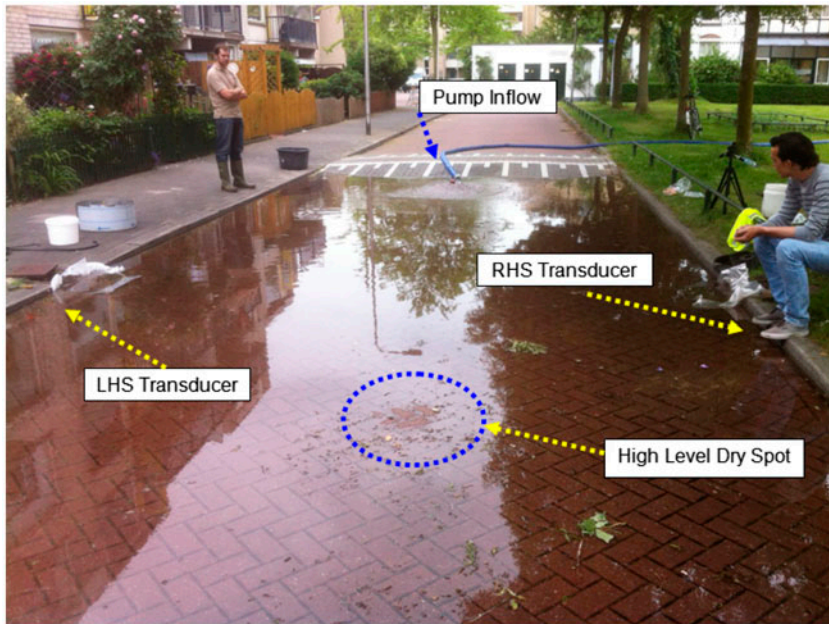


Figure 5. Pumping water on to test pavement area.

The water depths above the pavement were monitored using two different methods. Two wireless pressure transducers (Schlumberger Minidivers – shown in Figure 6) were installed at the lowest points on the LHS and RHS of the pavement (Figure 5). The transducers continuously monitored the standing water levels at their locations and these were transmitted and logged every second using a laptop computer. Manual water depth measurements were also recorded at the transducer locations over the duration of the testing to enable calibration and verification of the transducer readings.

For the CHFS method, the flowrate of the pump was increased in increments of approximately 0.50 l/s for a minimum period of five minutes until the applied flowrate was observed to be approximately equal to the infiltration rate. This point of equal infiltration and inflow was reached after approximately one hour and resulted in effectively constant storage and static water levels. The point of equal infiltration and inflow was deemed to occur just before the high point of the pavement surface was covered with water. Adjusting the water flowrate to control this was quite simple to do as it was easy to observe the dry surface area of the pavement becoming wet as the water level increased. The flowrate of the pump was measured by recording the time taken to fill a 50 litre container at the end of the inflow pipe. Repeated testing and verification of this volumetric measurement technique demonstrated it to be reasonably accurate ($\pm 3.0\%$) and reliable.

Once the equal infiltration and inflow flowrate value was established, this was used to calculate the CHFS surface infiltration rate. The dry area used to set the equilibrium flowrate is shown in Figure 5. The standing water levels at pavement locations RHS and LHS (Figure 5) were approximately 55 mm and 75 mm respectively at the equilibrium flowrate.

Double ring infiltrometer tests (DRIT) were also used at three locations over the test area. These included the same two locations as the pressure transducers (LHS and RHS



Figure 6. Middle double ring infiltrometer test (two minidivers can be seen in middle ring).

in Figure 5) and one location directly in the middle of the roadway between these two locations (High Level Dry Spot shown in Figure 5). The DRIT measurements were taken twice at each of the three locations to enable a comparison of the infiltration rates obtained from the other two methods. The time between each of the two tests was approximately 90 minutes. To ensure that the comparisons were realistic, only the last 70 mm and 90 mm respectively of the DRIT water level measurement results were used for the comparative analysis.

Results

FHFS infiltration testing results

The FHFS infiltration testing method was performed twice on the test permeable pavement used in this study in order to obtain the average infiltration rate over the whole pavement area. The second FHFS test (b) was performed approximately 90 minutes after the conclusion of the first test (a). For convenience, the timescales between testing have been shortened on Figure 7. The water level measurements for the lowest points in the pavement on the LHS and RHS of the street gutter are shown in Figure 7 along with respective linear regressions. Regression models and values are listed in Table 1.

CHFS infiltration testing results

The CHFS infiltration testing method was carried out as described in the Methodology section. The equilibrium flowrate was estimated at approximately 6.0 l/s using a reliable volumetric measurement method. This equates to an infiltration rate of 332 mm/h (or 923 l/s/ha) over the total 65 m² permeable pavement surface.

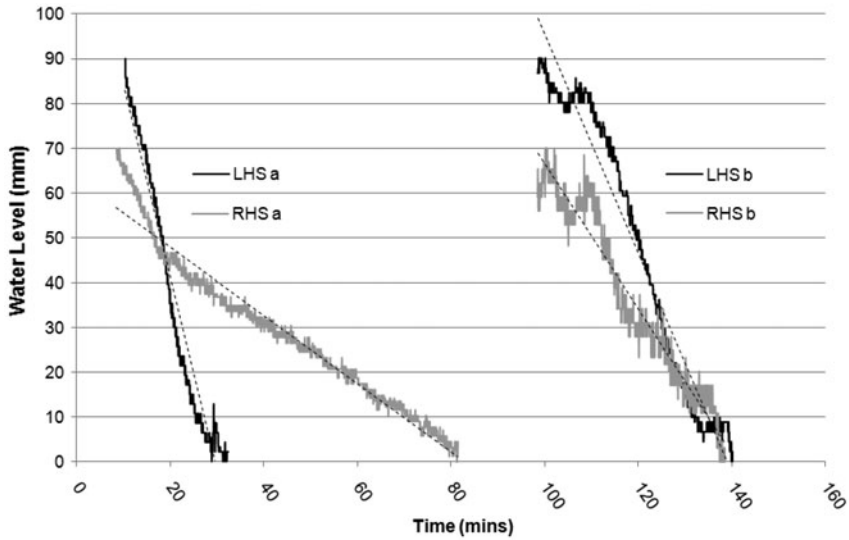


Figure 7. LHS and RHS pressure transducer readings for falling head infiltration tests.

Table 1. Calculated infiltration rates for all tests.

| Test | Location | Regression line equation | R ² | Infiltration rate (mm/h) | Median (mm/h) |
|------|---------------------|--------------------------|----------------|--------------------------|---------------|
| FHFS | LHS a | $y = -4.317x + 127.7$ | 0.956 | 259 | 122 |
| | RHS a | $y = -0.760x + 63.14$ | 0.961 | 46 | |
| | LHS b | $y = -2.444x + 339.8$ | 0.958 | 147 | |
| | RHS b | $y = -1.614x + 227.7$ | 0.947 | 97 | |
| DRIT | RHS a | $y = -12.67x + 61.13$ | 0.984 | 760 | 373 |
| | RHS b | $y = -6.005x + 61.37$ | 0.967 | 360 | |
| | Middle a | $y = -11.51x + 255.7$ | 0.995 | 691 | |
| | Middle b | $y = -6.442x + 166.8$ | 0.989 | 387 | |
| | LHS a | $y = -3.224x + 178.9$ | 0.987 | 193 | |
| | LHS b | $y = -1.582x + 120.2$ | 0.966 | 95 | |
| CHFS | Entire test surface | — | — | 332 | 332 |

DRIT results

The DRIT measurements were also taken twice at each of the three locations (LHS, Middle and RHS) on the test pavement area. These results are shown in Figure 8. The first of each of the DRIT tests was labelled test ‘a’ and the second of each of the tests was labelled test ‘b’ respectively (e.g. RHS a, RHS b). There was a break of approximately 90 minutes between the finish of the ‘a tests’ and the start of the ‘b tests’ at the three locations. However, for convenience and ease of comparison, the timescales between testing have been overlaid and shortened on Figure 8.

Tests labelled RHS a and RHS b in Figure 8 were undertaken at the same location as the RHS FHFS tests. Tests labelled LHS a and LHS b were undertaken at the same location as the LHS FHFS tests. Tests labelled Middle a and Middle b were undertaken in the middle of the test pavement.

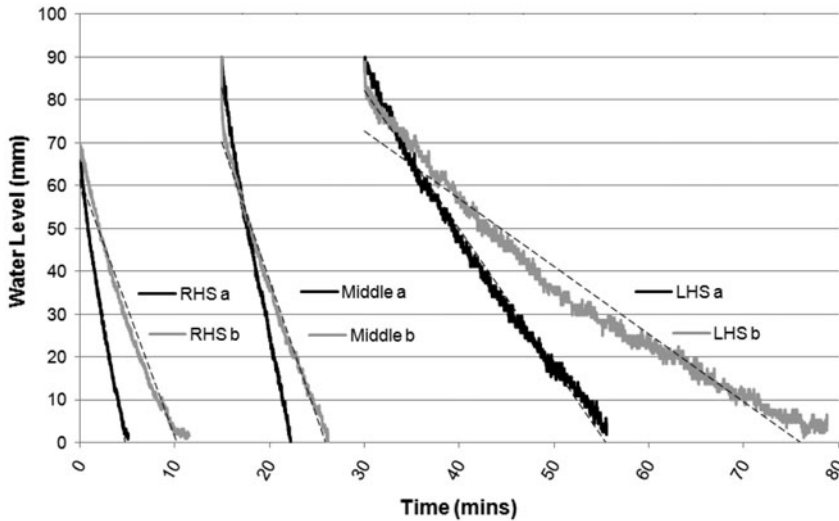


Figure 8. Double ring infiltrometer test results.

Calculated infiltration rates

Linear regression lines were added to the datasets in Figures 7 and 8 in order to enable a comparison of the general characteristics of the datasets and linear regression lines. This also enabled calculation of the average surface infiltration rates through the pavement at the respective locations using the slope of the regression lines. This information is shown in Table 1.

Discussion

Figure 7 shows a large a large variation in the water level results recorded for the second set of FSFH tests (b). The water levels readings for both the LHS b and the RHS b tests appear to increase between approximately 107 minutes and 112 minutes before dropping off again. They also both appear to flatten out for a short time around the 133 minute mark. The reasons for these fluctuations could not be ascertained with any certainty. One possible explanation for this is that the ambient air pressure may have fluctuated over the duration of the second tests and this could have caused variations in the pressure transducer, and hence the calculated water level readings. Pressure transducers are known to be highly sensitive and this may also have been the reason for the variations in the readings. This is an important issue that will need to be resolved in future research work.

The infiltration rates listed in Table 1 show a large variation between the three different infiltration testing methods. This is in agreement with previous studies that have attempted to quantify the infiltration rates of permeable pavements (Bean et al., 2007; Boogaard, Lucke, & Beecham, 2014; Kayhanian, Anderson, Harvey, Jones, & Muhunthan, 2012; Li et al., 2013; Lucke & Beecham, 2011). The infiltration rates for the FHFS inundation testing method vary between 46 mm/h and 259 mm/h, with a median value of 122 mm/hr. The measured infiltration rate for the second FHFS test for the LHS location was approximately 43% less than that of the first test. However, the

measured infiltration rate for the second FHFS for the RHS location was approximately 112% greater than that measured for the first test. The reason for this result could not be determined with any certainty. However, it was hypothesised that this may have occurred because the underlying media was more hydrophobic or contained different proportions of sand and clay particles from what was present at the other locations and this caused the media to react differently to initial wetting.

The infiltration rates listed in Table 1 for the double ring infiltrometer testing method vary between 95 mm/h and 760 mm/h, with a median value of 373 mm/hr. The infiltration rates for the second (b) tests at each of the three locations were all lower (between 44% and 53%) than the first (a) tests. It was hypothesised that this was due to the water from the first tests being absorbed by the clogged sediment and media underneath the pavement causing it to swell and effectively restricting water ingress. However, this also could not be confirmed unequivocally.

The large variations in the measured values listed in Table 1 demonstrate the difficulties involved in determining the correct surface infiltration rate value using different measurement techniques. The values obtained from the DRIT method were generally much higher than the results obtained using the FHFS method. However, it is clear that the infiltration results are highly dependent on the location where the testing is performed on the pavement surface. For example, Figure 7 shows the RHS as having a slower infiltration rate than the LHS for the FHFS tests. However, Figure 8 shows that the RHS has a faster infiltration rate than the LHS for the DRIT tests. The calculated infiltration results for the DRIT are also based on the infiltration rate through a very small area of the pavement. If these results are then used to represent the total pavement area infiltration this could lead to significantly inaccurate and unrealistic infiltration performance results.

In high intensity rainfall events, significant rates of water can fall on and run on to permeable pavement surfaces. This water then commences to infiltrate through the pavement surface until such time as the surface infiltration capacity is exceeded. Once the infiltration capacity is exceeded, the water level on the pavement surface will start to slowly increase and ponding generally commences at the lowest levels of the pavement surface. Ponding may also occur if the storage volume is filled and recovering at a slower rate than the infiltration. Ponding effectively increases the hydraulic head above the pavement and this can cause a slight increase in the infiltration rate through the lower pavement surfaces as ponding will flow to the localised lowest areas. However, there is a limit to this increase and if the rate of water flowing on to the pavement continues to increase, the water level will keep rising until the entire pavement surface is inundated. If this continues, water will eventually leave the system through kerb overtopping, or by diverted flow paths.

The median infiltration values listed in Table 1 also demonstrate the large variation in the results of the three different testing methods. The median value of the FHFS tests was 122 mm/h. This is only approximately one-third of the median value calculated for the other two test methods (DRIT = 373 mm/h and CHFS = 332 mm/h). The authors suggest that in this case it is probably more appropriate to use the more conservative median value obtained using the FHFS test method (122 mm/h) to represent the true value of the surface infiltration rate for the entire permeable pavement area tested in this study. The FHFS test has the potential to become widely accepted as the preferred method used to evaluate infiltration rates as it is relatively simple and cost effective to perform and appears to produce conservative, reliable and consistent results.

In the Netherlands, newly installed permeable pavements must demonstrate a minimum infiltration capacity of 270 l/s/ha, or 97.2 mm/h. Only one of the infiltration measurements listed in Table 1 is significantly less than this required value (FHFS – RHS a). This again demonstrates the dependence the measured infiltration results have on the pavement testing location. However, the measured infiltration rates shown in Table 1 generally demonstrate that the permeable pavement tested in this study would still be considered to be functioning satisfactorily in the Netherlands, even after seven years in service. Whether this infiltration rate would be satisfactory in other countries would depend on the local requirements.

Conclusion

This study has investigated a novel approach to assess the infiltration rates of permeable pavements that have been in service for over seven years. Two different new testing methods were investigated in the study, namely, the falling head full-scale (FHFS) method, and the constant head full-scale (CHFS) method. Both of the new methods involved inundating a large section of the pavement area in order to determine the infiltration rate through the pavement surface. Double ring infiltrometer tests (DRIT) were also performed to enable a comparison of the results.

The study found that the infiltration results obtained using the FHFS test method were probably the most appropriate to represent the actual infiltration rate of the whole pavement surface tested in this study. However, the study results suggest that the infiltration rates obtained for the study pavement using all three test methods would generally still be considered satisfactory in the Netherlands. Whether this infiltration rate would be considered satisfactory in other countries would depend on the local requirements.

The researchers plan to extend this study by undertaking testing on more pavements in the Netherlands, and also in other countries. One of the study findings was that using pressure transducers to measure water levels can produce inconsistent results. A more reliable way of measuring water levels above the test pavements is recommended for future studies.

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