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Measurement of Permeability and Comparison of Pavements

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Abstract: Permeable pavements have the ability to reduce surface runoff by allowing water to infiltrate into the underlying soil. The potential of permeable pavements to assist in managing stormwater and improve water quality has gained attention as an option, other than conventional impermeable concrete for paving purposes. This study examined the permeability of three different pavement systems, including the JW Eco-technology pavement (JW), which has not previously been installed or studied in the U.S., standard impermeable concrete (IC), and pervious concrete (PC). Each pavement type was installed in triplicate. Devices based on the ASTM C1701/C1701M and ASTM C1781/C1781M constant-head methods, the National Center for Asphalt Technology (NCAT) falling-head permeameter, and two new square frames, SF-4 and SF-9, modified to fit the JW pavement, were utilized for permeability measurement on several locations of each pavement system. The results showed that the JW Eco-technology pavement had comparable permeability to the commonly used PC pavement in each method used. In addition, there was a strong correlation between the permeability measurements of NCAT method and SF-4, and between the ASTM standard and SF-9. The square frames used in this study showed their effectiveness and efficiency in performing permeability measurements. It was also found that the permeability obtained had a pronounced difference in values between the falling head and the constant head methods, with an average ratio ranging from 4.08–6.36.

Keywords: JW Eco-technology; pervious concrete; permeable pavement; impermeable concrete; permeability; ASTM C1701/C1701M; ASTM C1781/C1781M; NCAT permeameter

1. Introduction

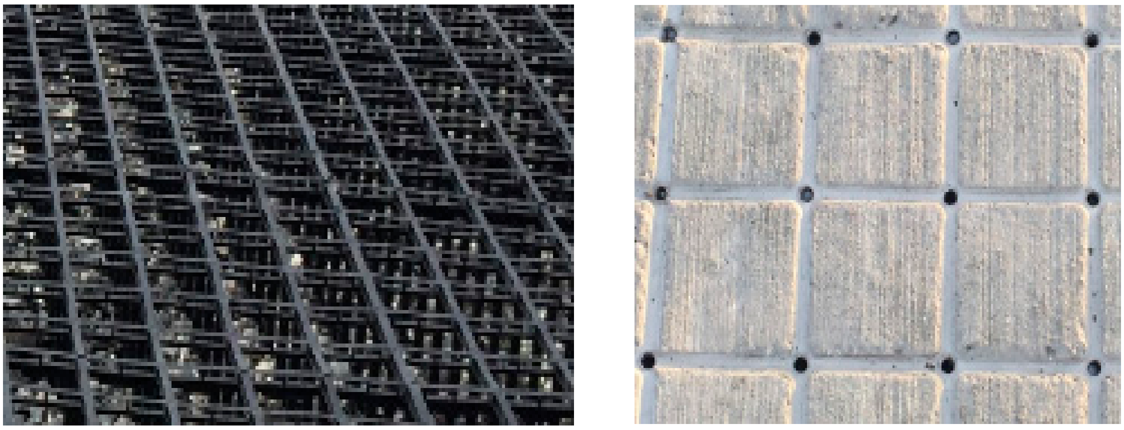
The world population is predicted to increase substantially and steadily in the coming decades [1], with the majority of people settling in urban areas [1,2]. As urbanization increases, consequently, it leads to the scene of urbanized areas with increased impervious surfaces [3–5]. Known environmentally related issues associated with the increased impervious areas include the heat island effect [3,4,6,7], increasing surface runoff and peak runoff rates caused by stormwater [3,5,8,9], and surface water pollution [5,8–11]. On the other hand, rainfall frequency, intensity, and amount are changing, and the frequency of floods and droughts are becoming more common in many parts of the world [3,5,12]. The risk of heavy precipitation and floods are projected to be higher when the temperature increases 1.5 °C from pre-industrial levels [12]. It is essential that societies prepare for impacts and hazards, due to urbanization and climate change, but the situation will continue in the absence of mitigation strategies. As an alternative to conventional impermeable pavements, permeable pavement are an option that may alleviate some negative impacts to the environment [3–11,13–18]. The benefits of permeable pavement make it an appealing best management practice (BMP) and low impact development (LID) method that is recommended for stormwater management in the U.S. [19]. Other stormwater management methods that have been developed include swales, bioretention basins, and wetlands. However, these other methods demand land, and they may not fit urbanized areas where space is restricted [18]. The use of permeable pavement is also in accordance with the concepts proposed in other countries, such as the sustainable urban drainage systems (SUDS) in the UK [20] and the water-sensitive urban design (WSUD) in Australia [21]. In addition, green building construction has become popular, and permeable pavement is one method that is mentioned by the U.S. Green Building Council (USGBC) for stormwater management in the Leadership in Energy and Environmental Design (LEED) rating system [22]. It is also recommended by EEWH, an evaluation system that includes four major categories—ecology, energy saving, waste reduction, and health for Green Building in Taiwan that launched in 1999 [23].

In general, common permeable pavements include, but are not limited to, pervious concrete, pervious asphalt, pervious pavers, permeable interlock concrete, and other pavers with plastic grids [3,15,18,24–26]. The general applications of permeable pavements include parking lots, driveways, and sidewalks, and have been used for rural roads where traffic loading is not heavy [3,27–30]. Since stormwater management is a constant challenge in urban environments, permeable pavements can also be used for the collection and storage of rainwater on-site, and for future use [31–34]. The infiltration of water into permeable pavement is dependent on the permeable pavement system that is used, as porous areas through which water flows to the subsurface layer vary. For example, the void area of pervious concrete ranges 15–25% in pervious concrete with mixtures by National Ready Mix Concrete Association (NRMCA) [35], and is between 14–31% from another report regarding a study about pervious concrete in a cold weather climate [36]. In general, the permeability of permeable pavement will also vary depending on the location, function, application design, and time elapsed after installation [3,13–15,26,37,38]. In a review paper, the permeability of 18 permeable concrete mixtures was in the range of 0.076–3.5 cm/s [15]. Tests of 40 permeable pavement sites in North Carolina, Maryland, and Delaware by Bean et al. [26] revealed the permeability rates of pervious concrete sites without fines ranged from 600 cm/hr to 7000 cm/hr. The permeability of pervious concrete sites with fines were significantly lower, and ranged from 11 cm/hr to 27 cm/hr. Permeability is a primary characteristic of permeable pavement that indicates its capacity to allow surface water to infiltrate into the lower layer. However, debris (i.e., from automobiles or the environment) may clog the pavement pores over time if not properly maintained [3,14,38–45]. When the pavement surface becomes fully clogged with debris, the top surface may require removal and replacement to achieve maximum permeability once again, which may pose an extra economic burden. On the other hand, studies have shown that not all clogging of permeable pavements cause significant reduction in permeability performance [44,45]. Permeable pavements must demonstrate a certain permeability capacity, or a threshold that indicates when maintenance is required in order to guarantee a hydrologic benefit [40,43]. The direct way of determining the permeability of a pavement system is to monitor the hydrologic performance [41–48]. A properly maintained permeable pavement may provide many environmental benefits and is a recommended pavement option [48].

Walloch et al. [49] pointed out that measuring the surface permeability in small areas was chosen by pervious concrete pavement industry partners, due to its manageability and low time requirement for the measurement. There are two primary principles that have been utilized to obtain permeability measurements in both the laboratory and in the field: the falling head and the constant head permeability tests. However, several studies highlight the inconsistencies of data generated. Two common methods for field measurement, the ASTM C1701/C1701M and the NCAT permeameter are based on the constant head and falling head methodologies, respectively. While the ASTM and NCAT methods were developed originally for permeable concrete and asphalt pavements, respectively, they have also been used to test other permeable pavement systems [50]. Li et al. [50] measured permeability using ASTM C1701/C1701M and NCAT permeameters in several experiments and found that the values from the ASTM method were 50–90% lower than those by the NCAT method, and the correlation observed between the data measured by the two methods was weak with R^2 = 0.52. Qin et al. [51] pointed out the difference in permeability of pervious concrete using the falling head and constant head methods and showed that permeability was dependent on applied water pressure on the test sample, and the permeability measured from the falling head method was higher than that from the constant head method at a laboratory test. Sandoval et al. [52] compared the permeability measurement between the falling head and the constant head tests on pervious concretes and found the falling head test expressed a high dispersion and could not assess the hydraulic potential that the materials actually presented. In addition, as there are several types of permeable pavements with surfaces consisting of different shapes, grid distributions, and designated orientations, cylindrical permeameters may not be best suited for these types of pavements. Methods that modify the existing standard methods have been attempted to determine permeability of various types of permeable pavement [26,43,53–56].

The modification of existing methods or the development of new methods should consider the ease of use, economic feasibility, and necessary time to complete the measurement [26,49]. Bean et al. developed a method for permeable interlocking concrete, pervious concrete, and concrete grid pavements utilizing a single ring infiltrometer [26]. Nichols et al. [54] used a modified double-ring infiltrometer and a specially designed rainfall simulation infiltrometer to examine the permeability of permeable interlocking concrete pavements and found that permeability obtained by the former method was 60% higher than the latter. Studies pointed out that the techniques and methods applied to determine permeability gave different values for the same field test location or same testing materials at the laboratory [38,50,51]. However, there is no consensus as to which existing standards should be used for measuring the permeability of permeable pavements. Li et al. [50] also highlight that a measurement constraint of permeability is that several terminologies, saturated hydraulic conductivity, infiltration rate, permeability coefficient, or simply permeability, appear interchangeably in the literature, and suggested that sticking to the use of consistent and standardized terminology should be considered, no matter what test method is used. In addition, as new mixtures and materials become available for permeable pavements, the method for measuring permeability will need to be matched to the type of pavement tested. In a paper reviewing pervious concrete, it was suggested that the laboratory–field correlations should be in the future research scope as most studies being carried out are restricted to laboratory conditions [15]. As permeability measurements are inconsistent between methods, it is necessary to perform comparative analyses and look for correlations between methods. Therefore, it is very important to document the permeability measurements along with information pertaining to the permeable pavement type, design, age, as well as whether a laboratory or field method was used. As more data are collected, the comparative analysis and correlation between methods can also be further investigated. Multiple runs are commonly needed to increase the accuracy and reliability of permeability measurements.

In addition to the common permeable pavement systems mentioned, the JW Eco-technology also recently gained attention. The JW Eco-technology pavement has been described in the literature as a load-bearing pavement because of its unique structure and design [3,57,58]. The JW Eco-technology product was first installed in the USA at the University of Illinois (Urbana-Champaign) in 2016, and it may provide a permeable pavement alternative that has the necessary structural strength needed for roadways, while also providing stormwater management and other environmental benefits. JW Eco-technology was developed in Taiwan by Mr. Jui-Wen Chen. JW refers to the initials of the inventor's first name. It has become an option to replace impervious concrete in many areas of Taiwan and China [59,60]. In Taiwan, a 10-year guarantee for the evenness and smoothness of the JW pavement is provided by the inventor [3]. JW Eco-technology combines the use of plastic frames and concrete to form its structure. Each unit of air-circulating aqueduct frame made of polypropylene (PP) forms the basic structure. Individual units of the frame are installed and leveled across a desired area, and concrete is then poured and evenly leveled over the frame. Each frame unit is covered by a plastic frame lid, so that the aqueduct openings will not be blocked when pouring concrete. The lid is peeled off when the concrete dries. After this procedure, the aqueduct frame is embedded in the concrete, which provides some reinforcement to the concrete. Figure 1 demonstrates an example of a completed JW Eco-technology unit.



(**a**) (**b**)

Figure 1. (**a**) The surface layer of JW Eco-technology aqueduct frame before concrete was poured; (**b**) an example of the finished JW Eco-technology surface.

The air-circulating aqueduct openings are evenly distributed among the concrete unit, approximately 100 pores per square meter [3,57]. The interior of each aqueduct surface is smooth, to allow surface water to flow directly along the interior wall downward to the subsurface layer. The JW Eco-technology prevents the occurrence of lateral flow that is seen in most permeable pavement systems [57]. Depending on the location and objective of a paved area, the design of the pavement using JW Eco-technology may vary. In general, the JW Eco-technology pavement is composed of a layer of the JW Eco-technology paving surface on top, and an underlying layer of gravel with designated thickness, and below are the soil base layers as shown in Figure 2. A prescribed number of JW Eco-balls, or plastic hollow balls that increase the storge capacity of water, are distributed throughout the gravel layer.

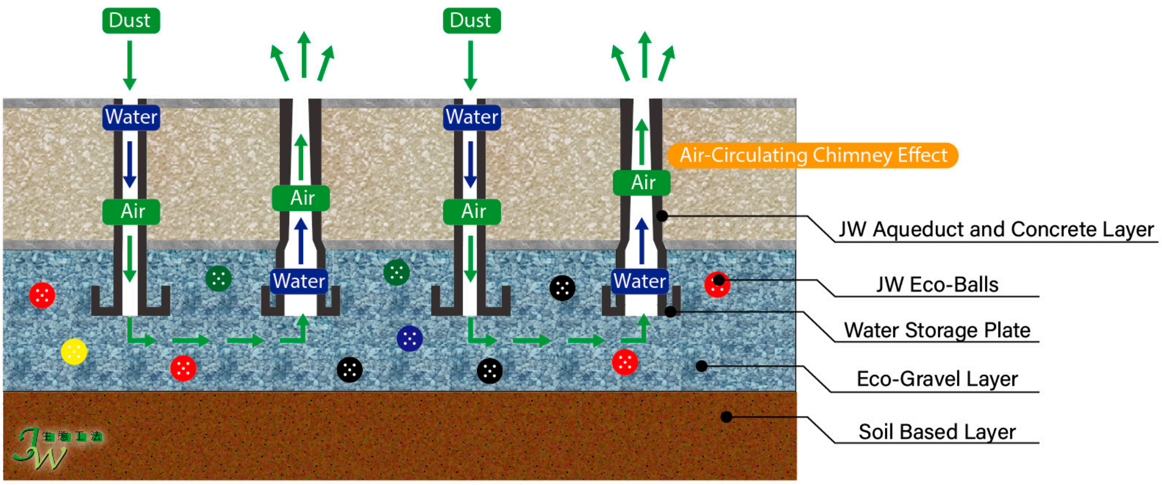


Figure 2. A typical pavement design using the JW Eco-technology method (courtesy of JW Eco-technology, Ding Tai, Co., Ltd., New Taipei City, Taiwan).

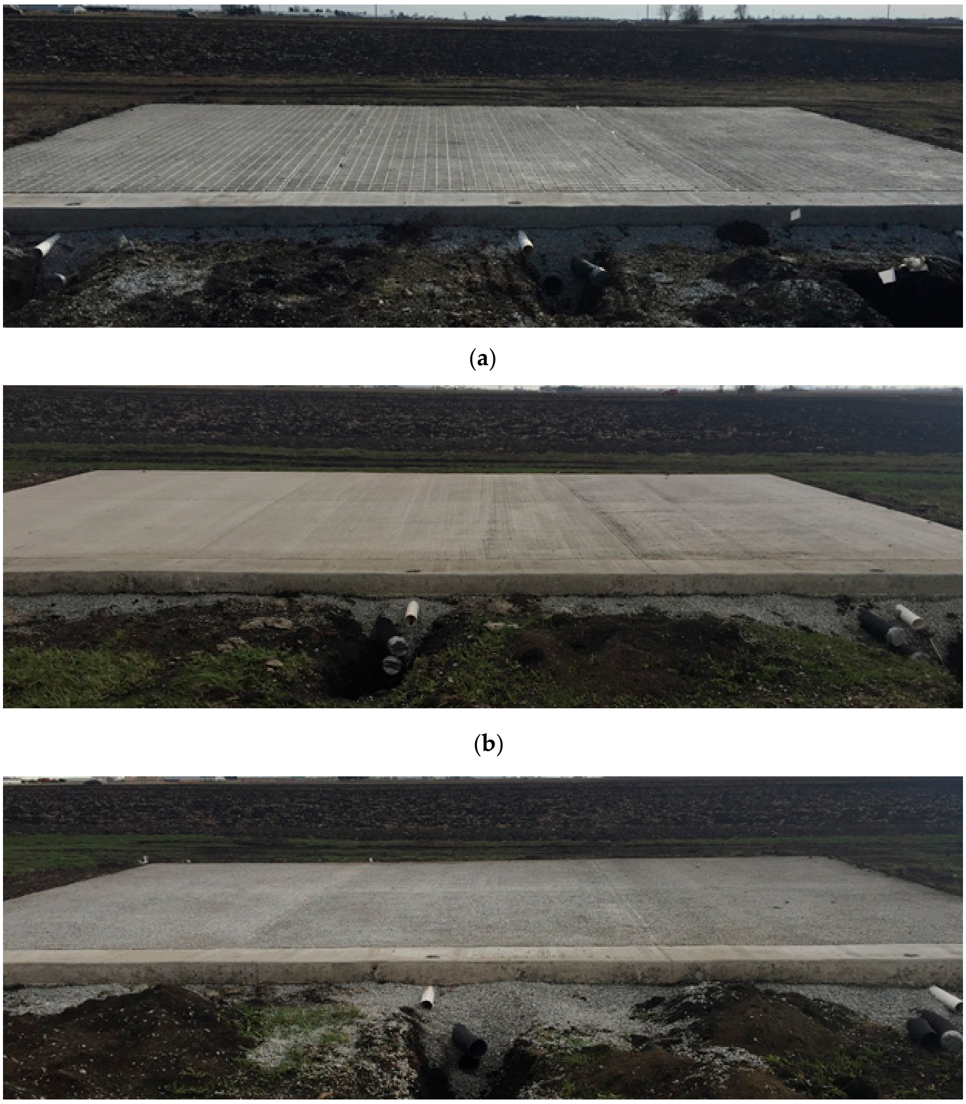
The JW Eco-technology has been tested successfully for 10 years at selected locations in Taiwan [3,57,58]. In Taiwan, JW Eco-technology pavement has been used for street sidewalks, pedestrian walkways, outdoor parking lots, squares, pedestrian walkways, and basketball courts. In addition, it has been installed at a harbor loading area where container trucks have run frequently for years without any problems. It is common to build rainwater collection units and retention tanks where the method is used. In addition, a 50 m length of JW Eco-technology road was constructed within the campus of the Taipei National University of Technology (TNUT). Since 2003, the road has maintained its integrity with no cracks or bumps, and the paved JW Eco-technology site maintained good permeable capacity after its completion without regular maintenance [3,57]. Liu et al. [3] also mentioned that with suitable maintenance, the JW Eco-technology pavement has the potential to operate at the initial design specification for more than 10 years in terms of smoothness, evenness, load-bearing, permeability, water storage, breathability, and underground ecosystem development. With these benefits, resources and extra expenses required for replacing the pavement could be reduced or even eliminated, it could be a sustainable pavement over a long time span. The JW Eco-technology is recommended for stormwater management and flood prevention by the official agency responsible for the green building certification [3]. More recently, while flooding caused by a tropical depression occurred in most areas in southern Taiwan in late August 2018, a campus located in southern Taiwan that had just completed installation of this JW Eco-technology was free from flooding. In a comparative investigation of ecological activities by analyzing samples collected under different permeable pavement systems installed side-by-side, Fan et al. [58] found that under the JW Eco-technology pavement, most microbial compositions and activities both surpassed those underneath the other permeable pavements, as did the abundance and diversity of bacterial communities. The soil under the JW Eco-technology pavement also exhibited more activated and versatile microbial metabolism in all substrates. The JW Eco-technology has become popular and has drawn attention in several countries and regions in the world. It has been used or will be used in places in China, Australia, and Africa for several different purposes [59,60]. However, the JW Eco-technology method was not used in the USA until the study and demonstration site for a series of investigations on pavement systems was built at the University of Illinois at Urbana-Champaign (UIUC) in November 2016.

2. Materials and Methods

In this study, the research group used three common standard methods and one new method, along with a new device, to determine the permeability of the three pavement systems at the project site. The pavement systems and the methods used are described in the following sections.

2.1. Study Site

It is often practical and desirable to replace impermeable paved areas with permeable pavement for certain uses to reduce the impervious area. Meanwhile, as more choices of pavement types are available, especially in urban areas, it is important to understand the effects of each pavement system, and how it will affect the environment. Located at the Agricultural Engineering Research and Training Center of the University of Illinois at Urbana-Champaign (UIUC), a project site for permeable pavement study was established. The overall goal was to investigate the environmental adapting capacity of various pavement systems. Three paving treatments, including the patented JW Eco-technology system (JW), conventional impermeable concrete (IC), and pervious concrete (PC), were utilized in this project, each of which was installed in triplicate. The study site, shown in Figure 3, was established in November 2016. It should be noted that there were no regular traffic loadings or activities that subjected the site to routine sediment loadings or clogging. Therefore, the project site was presumed to represent three newly installed pavement systems at the time when this study occurred.



(**a**)

(**b**)

(**c**)

Figure 3. The pavement study site at the University of Illinois Urbana-Champaign is equipped with three pavement types, from top to bottom, (**a**) JW, (**b**) IC, and (**c**) PC pavement systems.

Permeability is a direct indication of the ability of a pavement to absorb water, which leads to the judgment of the necessity of maintenance. As the applications and the use of permeable pavement become more common, a promising tool that can be used to determine the permeability of pavement systems is needed. Before the achievement of the goal, the measurement of permeability of different pavement systems that follows existing standards should be considered. In another aspect, the comparatively new concept, the JW Eco-technology pavement surface has a grid distribution of holes with specific dimensions. Therefore, one or more new or modified methods that fit this specific pavement are needed. The objective of this study was to assess and compare the permeability measurements of three different pavement systems, using both currently recommended methods and new methods using a square frame built to specifically match the JW aqueduct spacing.

2.2. Pavement Systems

The study site includes three pavement systems; pervious concrete, conventional impermeable concrete, and the patented JW Eco-technology method, and each is in triplicate for nine total pavement pads. The dimensions of each pavement pad are 6.10 m × 3.05 m (20 ft × 10 ft) with a 0.305 m (1 ft) buffer strip between the three replicates of the same paving material. Therefore, the existing triplicate pads with the same materials appear as a whole slab; however, the surface and subsurface drainage water are kept separate for each of the three pads by a small surface barrier and a visqueen liner, respectively. The orientation of each pad is in a north–south direction, with a 2% slope from south to north, which will drain surface water to the collection units. The distance between pavement types is 6.10 m (20 feet). There are two perforated tiles beneath each pavement plot (three plots per pavement pad), one at the designated soil layer, and the other at gravel layer, under each of the nine pads. The tiles direct subsurface water to the collection equipment. In addition, there is a 9.75 m × 0.61 m (32 ft × 2 ft) concrete v-trench with three drainpipes at the north end of each paving slab. These trenches allow the surface water on each pad to flow to the outlet drain and then to the collection tank. The overview of the installed pavement site is illustrated in Figure 4.

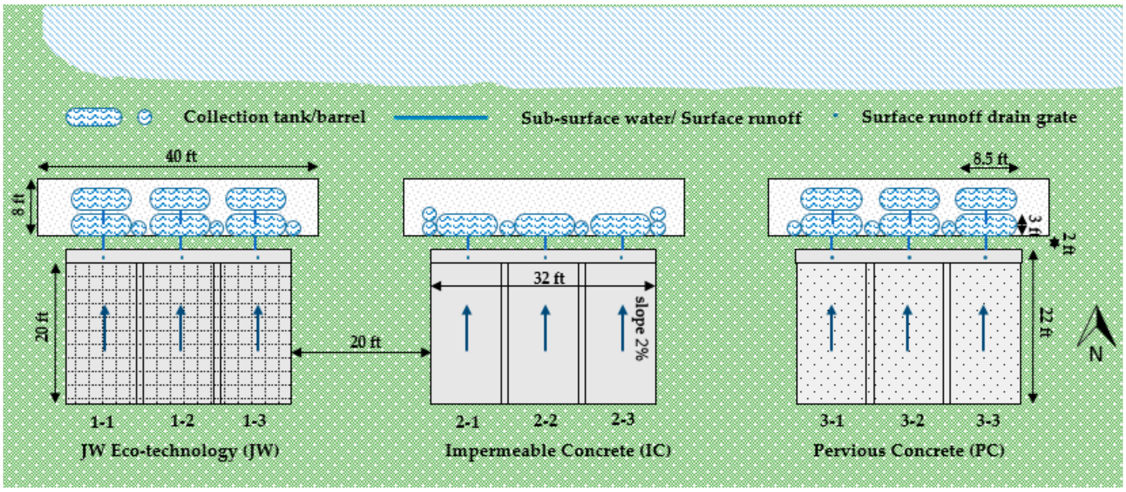


Figure 4. Overview of the three pavement systems at the project site, from left to right, JW Eco-technology, impervious concrete, and pervious concrete.

2.2.1. JW Eco-Technology

The installation of the patented permeable pavement (JW) followed the standard procedure, which was provided by the inventor Mr. Jui-Wen Chen, who was onsite to provide consultation during installation. The cross-sectional profile of each of the JW Eco-technology plots consists of two 20.32 cm (8-in) subsurface layers. The paving surface of the JW Eco-technology consists of two components, the assembled JW aqueduct mold frame, and 15.24 cm (6 in) of class SI concrete. The installation procedure included the excavation of 55.88 cm (22 in) of soil and the placement of 8-Mil (eight thousanths of an inch) visqueen on the bottom of each excavated area. The visqueen was extended to cover 55.88 cm (22 in) vertically on all sides of the proposed excavation to contain the drainage water from each pavement plot, and to prevent the water table from contributing to the drainage water of a given plot. A 10.16 cm (4-in) diameter perforated high-density polyethylene (HDPE) drain tile with sock was installed near the bottom of the soil layer for the collection of subsurface drainage water, backfilled with 20.32 cm (8 in) of excavated earth, compacted, and backfilled with another 10.16 cm (4-in) diameter perforated HDPE drain tile with sock in the gravel layer for subsurface water drainage and collection from this layer.

The placement of the gravel layer was completed by spreading and flattening the mixture of 1 × 3-in aggregate and CA-14 aggregate into the plot. This step created a flat and firm base for the gravel layer, which was followed by spreading JW eco-balls evenly on the gravel base. The hollow eco-balls are used in the JW method to increase water storage capacity at the gravel layer. The remainder of the gravel mixture was added to achieve a total depth of 15.24 cm (6 in) of aggregate and topping it with another 5.08 cm (2 in) of CA-14 aggregate. The total depth of the gravel layer was 20.32 cm (8 in).

The assembled JW aqueduct frame was placed on the established gravel base. After all subsurface layers of the three plots were completed, the paving surface was installed by placing 15.24 cm (6 in) of Class SI non-reinforced concrete into the JW Eco-technology mold structure. When the concrete was near dry, the lids covering the aqueduct openings were peeled and discarded. The cross sections of the JW Eco-technology pavement, along with the impermeable concrete and the pervious concrete, are shown in Figure 5.

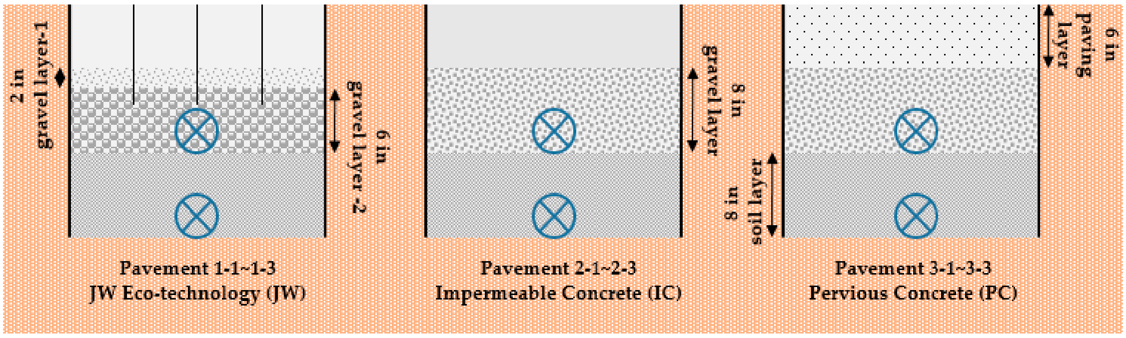


Figure 5. Cross-sections of the three pavement systems.

2.2.2. Impermeable Concrete

The cross-section profile of each of the impermeable concrete plots consists of two subsurface layers, the 8-in soil layer at the bottom, and on top the 20.32 cm (8-in) gravel layer with CA-6 gravels. The surface is furnished with 15.24 cm (6-in) of Class SI concrete. The installation procedure for excavation, the placement of the visqueen, and the setting of perforated HDPE drain tile with sock was the same as that described previously for the JW pavement. After all subsurface gravel and soil layers of the three plots were completed, the paving surface was finished by pouring 15.24 cm (6 in) of Class SI concrete. When the concrete was nearly dry, each concrete pad was cut at the midpoints of the east–west orientation to create expansion joints, to allow for compensation when the concrete shrinks or expands due to the changes in temperature.

2.2.3. Pervious Concrete

The cross-section profile of each of the pervious concrete plots also consists of two subsurface layers, the 20.32 cm (8 in) soil layer at the bottom of the underlying soil, and the 8-in gravel layer with CA-7 limestone between the soil layer and pavement. The surface was furnished with a layer of 15.24 cm (6 in) pervious concrete. The installation procedure including the excavation, the placement of the visqueen, and the setting of perforated HDPE drain tile was also the same as described for the JW Eco-technology and impermeable concrete pavement systems. After all subsurface layers of the three plots were completed, the paving surface was furnished by pouring 15.24 cm (6 in) of pervious concrete on top. Pervious concrete is generally a mixture of water, cement, and large aggregate, with little or no sand, and fine aggregate. The coarse aggregate with little room for particle packing allows for the creation of void content. Also, consolidation was performed by a steel roller working over the concrete surface to compact and flatten the surface. When the concrete was nearly dry, each concrete pad was cut at the midpoints of the east-west orientation to create expansion joints. As with the impermeable concrete, this was to allow for compensation when the concrete shrinks or expands due to changes in temperature.

2.3. Testing Methods

2.3.1. NCAT Permeameter

The first method used in this study is the NCAT method, based on the falling-head principle. The permeameter design and test protocol for field testing of asphalt permeability was developed by the National Center for Asphalt Technology (NCAT) [61]. It uses Darcy's Law to determine the rate of water flow through asphalt pavement, and has adjustments for testing permeable pavements with different porosities. The NCAT permeameter consists of up to 4-tiered graduated standpipes with different inner diameters. Area values from the top to bottom tier are 2.85 cm^2, 15.52 cm^2, 38.32 cm^2, and 167.53 cm^2, respectively. The different tiers allow users to select a tier that best fits the desired test, in terms of estimated permeability. The choice of tier depends upon the flow rate at which the water level is falling after the cylinder is filled with water. The uppermost tier allows quick determinations in pavements with low porosity. Pavements with high permeability will necessitate selection of one of the larger diameter tiers because the head will fall too quickly for accurate observation in the smaller diameter tiers. In general, the bottom tier with the largest diameter allows enough time to accurately determine the permeability in pavements with a more porous structure. The coefficient of permeability can be determined by the time elapsed and the decrease in water level. The relationship is expressed in Equation (1):

$$K = \left(\frac{aL}{At}\right) \times \ln\left(\frac{h_1}{h_2}\right), \quad (1)$$

where K = coefficient of permeability, cm/sec; a = inside cross-sectional area of the standpipe, cm^2 (the value varies depending on tier used for testing); L = length of the sample, cm (effective thickness of the test material); A = cross-sectional area of permeameter through which water can penetrate the pavement (test area) cm^2; h_1 = Initial (upper) head, cm; h_2 = Final (lower) head, cm; t = elapsed time between water falling from h_1 to h_2. In this study, the Gilson AP-1B NCAT Asphalt Field Permeameter by Gilson Company, Inc. (Lewis Center, OH) was used, as shown in Figure 6. It consists of the bottom two tier tubes with marked graduations, and the base. A rubber gasket on the bottom of the base plate ensured a well-defined area for the permeability test.

(**a**) (**b**)

Figure 6. (**a**) The structure of the NCAT permeameter used in this study. (**b**) Usually, some weights were placed on the base to stabilize the instrument and to help secure the seal between the instrument and the test pavement.

The overall operating procedure is (1) select and clean the test area to enable a watertight seal, (2) to mold and place a uniform layer of plumber's putty around the outside diameter, (3) position the instrument on the test location and apply uniform foot pressure around and add four weights on the perimeter of the base, (4) test for leakage, reseal the base and the pavement surface as necessary until no leakage is observed, (5) start permeability measurements and record the data.

It should be noted that several assumptions were made using this method. First, the test section was pre-wetted with approximately 3.875 L (1 gallon) of water before testing, but the flow of water was not impeded and was assumed saturated during testing. Second, the water flow through the pavement was assumed to be laminar. Also, the effective thickness of test sample was the thickness of the porous layer of the pavement. For consistency and uniformity with administering the permeability tests, each test location was completed by one operator. It was found that not every test was successful without leakage. As water leakage affects the permeability test results, the tests were repeated until no leakage was observed. It is important to fill water at a uniform rate. Careful filling ensures a minimum of bubbles and entrapped air in the water column. Test times vary greatly depending on mix gradation and density, but they should generally not exceed five minutes. As the permeable pavements in this study exhibit high permeabilities, the operator selected the bottom tier of the standpipe for the permeability tests. Also, the starting and ending of water levels were in the same tier, the bottom tier; therefore, the parameters a and A in Equation (1) are equal, and the calculation of saturated hydraulic conductivity can be simplified to Equation (2):

$$K = \left(\frac{L}{t}\right) \times \ln\left(\frac{h_1}{h_2}\right), \tag{2}$$

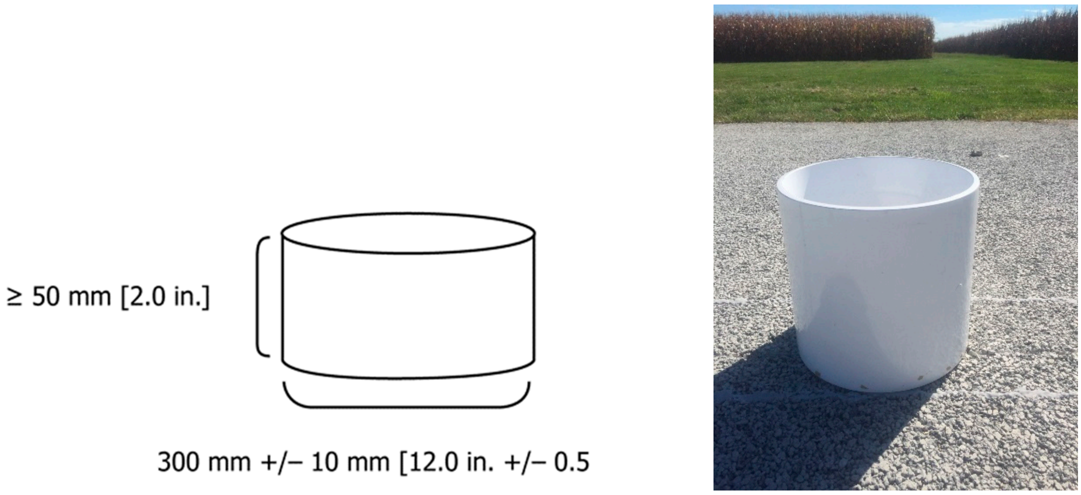
2.3.2. ASTM C1701/C1781M and C1781/C1781M Standards

ASTM C1701/C1701M was used to test the permeability on the permeable concrete pad, while ASTM C1781/C1781M methods was selected to test permeability on the JW and IC pad. The ASTM subcommittee C09.49 developed the C1701/C1701M Standard Test Method for the Infiltration Rate of In Place Pervious Concrete. The standard is issued under the fixed designation C1701/1701M. The current edition was approved and published in 2017 [62]. The ASTM subcommittee C15.04 developed C1781/C1781M Standard Test Method for the Surface Infiltration Rate of Permeable Unit Pavement Systems. This current edition was approved and published in 2015 [63]. The Test Method C1781/C1781M is functionally identical to the Test Method C1701/C1701M, but it includes the added provisions for positioning and securing the test ring to a discontinuous surface. Both test methods should give comparable results [62,63]. Different from the falling head principle that governs the NCAT principle, both ASTM C1701/C1701M and ASTM C1781/C1781M standards are applying a constant head principle. The summary of ASTM C1701/C1701M test method is to place and seal an infiltration ring to the surface of a permeable pavement system, and after pre-wetting the test location, a given mass of water is introduced into the ring and the time required for the water to infiltrate the pavement is recorded. The infiltration rate can be determined by applying Equation (3):

$$I = \frac{KM}{D^2 t}, \tag{3}$$

where I = infiltration rate in mm/hr; M = mass of infiltrated water in kg; D=inner diameter of infiltration ring, in mm; K = 4,583,666,000 $mm^3 \cdot sec/kg \cdot hr$; t = time required for water to infiltrate, in seconds.

ASTM C1781/C1781M targets discontinuous unit pavement systems, such as solid interlocking concrete paving units, concrete grid paving units, or clay paving brick, with joints and openings. These pavements allow drainage through joints between the units or through voids formed by the intersection of two or more units, or intentionally manufactured into the units. The permeability of the JW pavement system was measured using this method. The results of this test method for unit pavement systems can be compared to that using ASTM C1701/C1701M for pervious concrete. When performing either of the two standards, it is important that the infiltration ring be watertight, sufficiently rigid to retain its form when filled with water, and the bottom edge of the ring shall be even. As shown in Figure 7, the dimensions of the infiltration ring specified by the method shall have a diameter of 300 $\pm$ 10 mm (12.0 $\pm$ 0.5 in.) with a minimum height of 50 mm (2.0 in.). A watertight polyvinyl chloride (PVC) cylindrical ring with an inside diameter of 310 mm (12.25 in), and with openings at both ends was employed for both ASTM C1701/C1701M and ASTM C1781/C1781M standards. The inner surface of the ring was marked with two lines at a 10 mm and 15 mm (0.40 in and 0.60 in.) from the bottom of the ring. As each pad has a ~2% slope, the water level was maintained between the two marked lines at the lowest point of the slope when performing test. In addition, a stopwatch was used to record the time, and a 5-gallon plastic cylindrical container was prepared to fill with the water required for the test from a 1,000-gallon onsite storage tank.



(**a**) (**b**)

Figure 7. (**a**) Dimensions of infiltration ring described in ASTM C1701/C1701M and ASTM C1781/C1781M [62,63], and (**b**) the cylinder ring used in this study.

The complete methodology for measuring permeability is included in ASTM C1701/C1701M [62]. However, a summary of the procedure is included here: (1) clean the test location, (2) apply plumber's putty around the bottom edge of the infiltration ring, and set the ring onto the pavement surface being tested, (3) pre-wet the test location as specified in this method, (4) perform the test within 2 min after the completion of the pre-wetting, (5) start measurements and record the data, and (6) calculate the infiltration rate by using Equation (3). While the procedures described in ASTM C1701/C1701M and ASTM C1781/C1781M are similar, the following step was required when setting the cylindrical ring on the test location using ASTM C1781/C1781M [63]. It was noted in the standards that the drainage area within the infiltration ring was typically within ±20% of the average drainage area of the pavement as a whole. As JW has aqueduct openings that are evenly distributed on the pavement surface, it was comparatively easy to select the pattern that was able to include the most possible openings within the cylinder ring.

After this positioning procedure, plumber's putty was applied around the bottom edge of the infiltration ring, and the ring was set onto the pavement surface. As ASTM C1781/C1781M aims to test discontinuous unit permeable pavement systems, the procedure above for selecting and documenting the placement of the infiltration ring on a representative area of the pavement is sufficient in most cases, for determining the infiltration rate of the pavement. Since the aqueduct openings in the JW Eco-technology pavement are not connected, the drainage area is estimated by counting the number of voids in a given area. This assumes that the voids are designed to be consistent in size across the field of the pavement. In the appendix of the ASTM C1781/C1781M standard, a more accurate quantification of the infiltration rate can be obtained by normalizing the drainage area within the infiltration ring to the average drainage area of the whole pavement, expressed in Equation (4):

$$I = \left(\frac{KM}{D^2 t}\right) \times \left(\frac{DVPA}{DVTA}\right), \quad (4)$$

where DVPA is the number of drainage voids per area of pavement, in voids/m^2 (voids/ft^2); DVTA is the total number of drainage voids per area of the infiltration ring, voids/m^2 (voids/ft^2). It was determined that DVPA is 170.13, while DVTA is 118.32 for JW. The value of $\left(\frac{DVPA}{DVTA}\right)$ is about 1.44. Equation (4) is rewritten as Equation (5):

$$I = 1.44\left(\frac{KM}{D^2 t}\right), \tag{5}$$

2.3.3. Square Frame

This method was designed to accommodate the unique features of the JW pavement, but was additionally used on the other two pavement systems, as well to compare the consistency of the data obtained by ASTM and NCAT methods. This square frame method modified some of the materials and specifications described in the ASTM and NCAT permeameter methods. Two designated sizes of 30.48-cm (1-ft) tall Plexiglas square frames used in this study were made by Illini Plastics Supply (Champaign, IL, USA), dimensions of which, from small to large, are 12.9 cm × 12.9 cm (5 1/16 in × 5 1/16 in), and 23.5 cm × 23.5 cm (9 1/4 in × 9 1/4 in). Based on the designs, the frames covered areas of 165.4 cm^2 (25.6 in^2), and 552.0 cm^2 (85.6 in^2), respectively. The two square frames are named, from small to large, SF-4, and SF-9, respectively, as the main point of the design aims to include four, and nine aqueduct openings of JW Eco-technology, respectively. The square frame device acted as the infiltration ring in the ASTM method, and as the permeameter in the NCAT method. In this study, the SF-9 frame was used to perform the constant head principle based on the ASTM method, since both included nine aqueduct openings of JW in each of the testing locations. The SF-4 frame was used to perform the falling head principle based on the NCAT method, since both included four aqueduct openings of JW Eco-technology in each of the testing locations. The graduation levels for constant head measurement and falling head measurement were marked on each of the square frame boxes.

As this is a new method, some modifications were made as follows: (1) the initial head and final head using the falling head principle were fixed values in all tests, and (2) the amount of water consumed using the constant head principle per test was 18 kg, regardless of the results in the prewetting status. The data obtained with SF-4 that followed the falling head principle were calculated using Equation (2), as the test area was the same as the area covered by SF-4. Data obtained with SF-9 that followed the constant head principle were calculated by the Equation modified from Equation (3) by replacing the diameter with area (A), as shown below in Equation (6):

$$I = \left(\frac{\pi}{4}\right)\left(\frac{KM}{At}\right), \tag{6}$$

It is noted that the ratio of DVPA, the number of drainage voids per area of pavement, and DVTA, the total number of drainage voids per area of the infiltration ring, was not applied to this calculation, as the two ratios were the same, and therefore cancelled out.

2.4. Test Location

There have been no regular traffic loadings, so that the maintenance plan so far was to remove obvious substances on-site with the routine use of a leaf blower. The investigation of permeability was performed on sunny days when there was no rain within the previous 24 hr, and also no standing water on top of the pavement pads. The NCAT and ASTM methods were performed during August and September 2018, while measurements using the square frames (SF) were conducted in October 2018. The same test locations were used for all permeability testing methods. The measurements of field permeability of the three pavements were performed on the north and south sections of each pad, locations of which are shown in Figure 8.

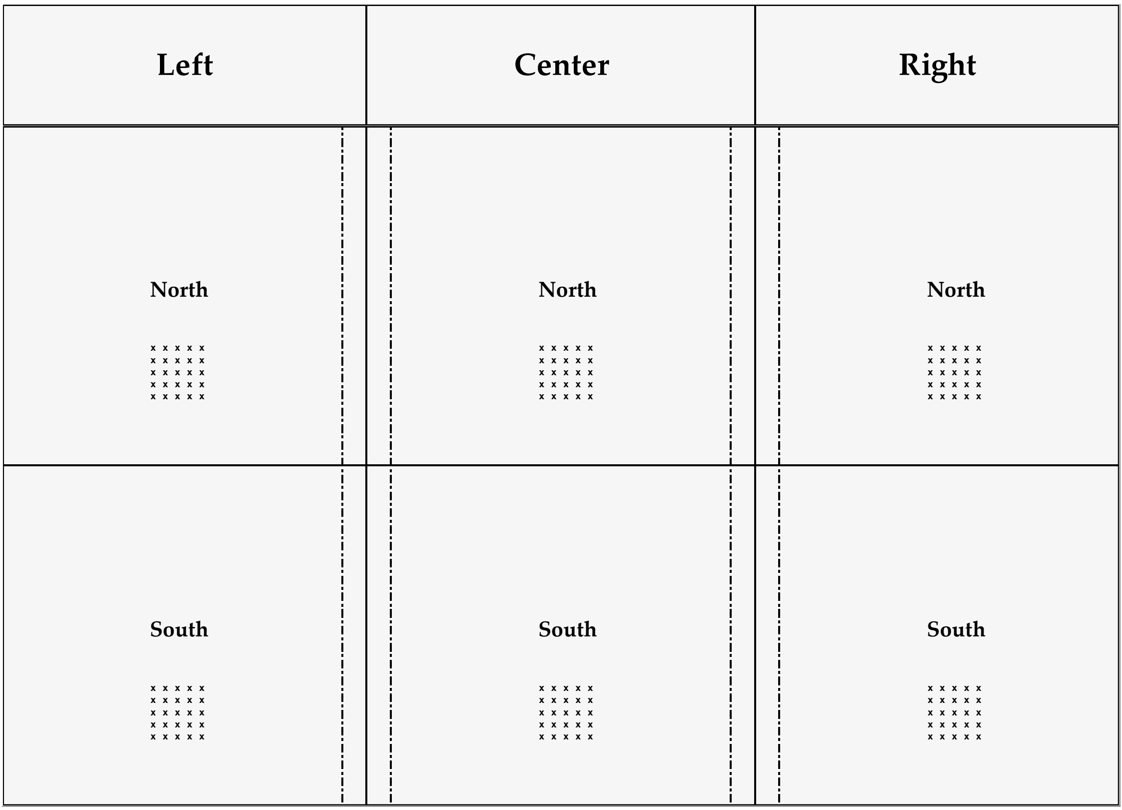


Figure 8. Permeability test locations, marked in red, on each type of the pavement pad.

2.5. Data Analysis

For each test location on the three pavement types, a descriptive statistics analysis was used to interpret and describe the basic features of the data collected using the ASTM and NCAT methods, as well as the data obtained with the two square frames SF-4 and SF-9. Linear regression analysis was utilized to explore the correlations among the testing methods used.

3. Results

The permeability of the impervious concrete pad, as expected, was negligible, according to each of the methods used and is therefore not presented. Permeability is not commonly tested on impervious surfaces, but will be briefly discussed later. The permeability measurements for the two permeable pavements, JW Eco-technology (JW) and pervious concrete (PC), are summarized in Table 1. Overall, JW showed comparable permeability with that of the pervious concrete in each method used. Based on the data measured with the NCAT method, the JW pavement had an average permeability between 4.40 cm/s and 4.75 cm/s, and between 0.89 cm/s to 1.00 cm/s with the ASTM method. The PC pavement had an average permeability ranging from 4.16 cm/s to 5.18 cm/s, and from 0.66 cm/s to 0.89 cm/s, based on the measurement with the ASTM method. There were no clear trends or differences with respect to the test locations. As for the permeability obtained using the square frames SF-4 (falling head principle) and SF-9 (constant head principle), in general, the data pattern was similar to that measured with the NCAT (falling head principle) and ASTM (constant head principle) methods, respectively. The JW pavement with the SF-4 method had an average permeability between 5.88 cm/s to 6.29 cm/s, and between 0.94 cm/s to 1.02 cm/s, with the SF-9 method. The PC pavement had an average permeability ranging from 3.17 cm/s to 5.13 cm/s, with the SF-4 method, and from 0.93 cm/s to 1.08 cm/s with the SF-9 method.

Table 1. Mean permeability (cm/s) of JW pavement and pervious concrete (PC) pavement measured on six different locations with NCAT (falling head principle), ASTM (constant head principle), square frames SF-4 (falling head principle) and square frame SF-9 (constant head principle). The measurement was the number of permeability measurements performed on each test location.

Method	NCAT		ASTM [1]		Ratio (NCAT/ASTM)	
Pavement	**JW**	**PC**	**JW**	**PC**	**JW**	**PC**
Mean	4.66	4.74	0.93	0.75	4.99	6.36
Max	6.73	5.90	1.13	1.11	5.96	5.32
Min	3.52	3.00	0.79	0.56	4.48	5.36
Stdev	0.68	0.65	0.08	0.14	8.10	4.65
Measurement	10	10	7	7		
Method	**SF-4**		**SF-9**		**Ratio (SF-4/SF-9)**	
Pavement	**JW**	**PC**	**JW**	**PC**	**JW**	**PC**
Mean	6.15	4.02	1.07	0.99	5.74	4.08
Max	6.88	5.95	1.30	1.16	5.27	5.11
Min	5.16	2.90	0.93	0.86	5.54	3.38
Stdev	0.49	0.92	0.08	0.08	5.73	11.03
Measurement	6	6	6	6		

[1] The JW pavement was measured using the ASTM C1781/C1781M standard, while the PC pavement was measured using the ASTM C1701/C1701M standard.

4. Discussion

The permeability measurements were collected using several methods in this study. The data highlight the large difference in the permeability values obtained with the ASTM and NCAT methods. The new methods that utilized the SF-4 frame (calculated by NCAT falling head formula) and SF-9 frame (calculated by ASTM constant head formula) also revealed a similar trend. Descriptive statistics of the permeability measurements are shown in the boxplots in Figure 9. The NCAT permeameter produced measurements that were several times higher than those from the ASTM permeameter at each test location. A similar observation was made on the comparison of measurements using the square frames, SF-4 and SF-9. The permeability from the SF-4 frame produced measurements that were several times higher than those from the SF-9 frame at each test location. Since this trend held for both PC and JW, this implies that the difference was not because of the pavement type, nor was it related to the test spots. Furthermore, the box plots suggest that the range of measured permeability was narrower using the ASTM and SF-9 methods, than that using the NCAT and SF-4 methods, respectively. The distribution of the permeability values measured in this study may be categorized into two groups, the falling head-based methods, or values calculated by NCAT formula, and the constant head-based methods, or values calculated by ASTM formula. The permeability measured with the two methods using the NCAT formula was much higher than those collected using the ASTM formula, regardless of the pavement type and test locations. Also, the permeability obtained with the ASTM method indicated that the JW pad in general had comparatively higher values than PC pad. As for the permeability obtained using SF-4, the JW pad also showed a permeability that was about 1–3 cm/s higher than that of the PC pad.

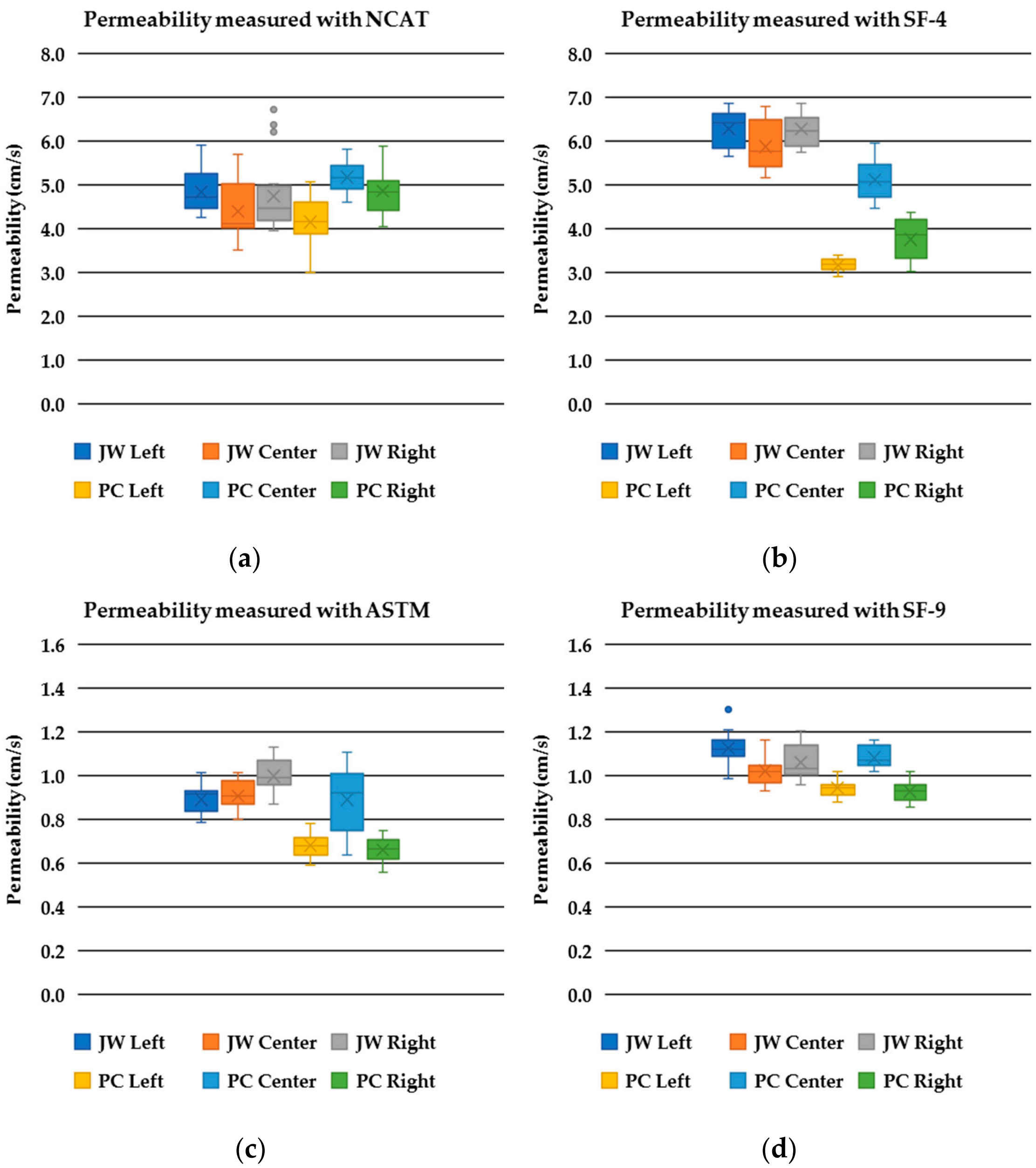


Figure 9. Descriptive statistics with the aid of box-and-whisker diagrams of the permeability measured with (**A**) NCAT (falling head), (**B**) SF-4 (falling head), (**C**) ASTM (constant head), and (**D**) SF-9 (constant head). Note the *y*-axis values for (**A**) and (**B**) range from 0–8 cm/s, while the values for (**C**) and (**D**) range from 0–1.6 cm/s.

The data collected in this study were further analyzed, to compare the permeability across methods. The mean values of permeability of north and south test locations were applied to this analysis. The comparison of permeability between the NCAT method and square frame SF-4, and between ASTM and square frame SF-9 methods, and between ASTM and NCAT, and the two square frames were investigated. Scatter plots of permeability were used to display the trend between the methods compared.

Scatter plots of permeability were used to display the relationships between the methods compared. According to Figure 10, the data showed the permeability measured with SF-4 was higher than that with the NCAT method for the JW pavement. The measurements from SF-4 were higher than those obtained from the NCAT method calculated by the same formula. Also, the permeability measured with SF-9 was higher than that with the ASTM method on the JW Eco-technology pavement system. It was found that the difference between SF-9 and ASTM in permeability was smaller than that between the SF-4 and NCAT methods.

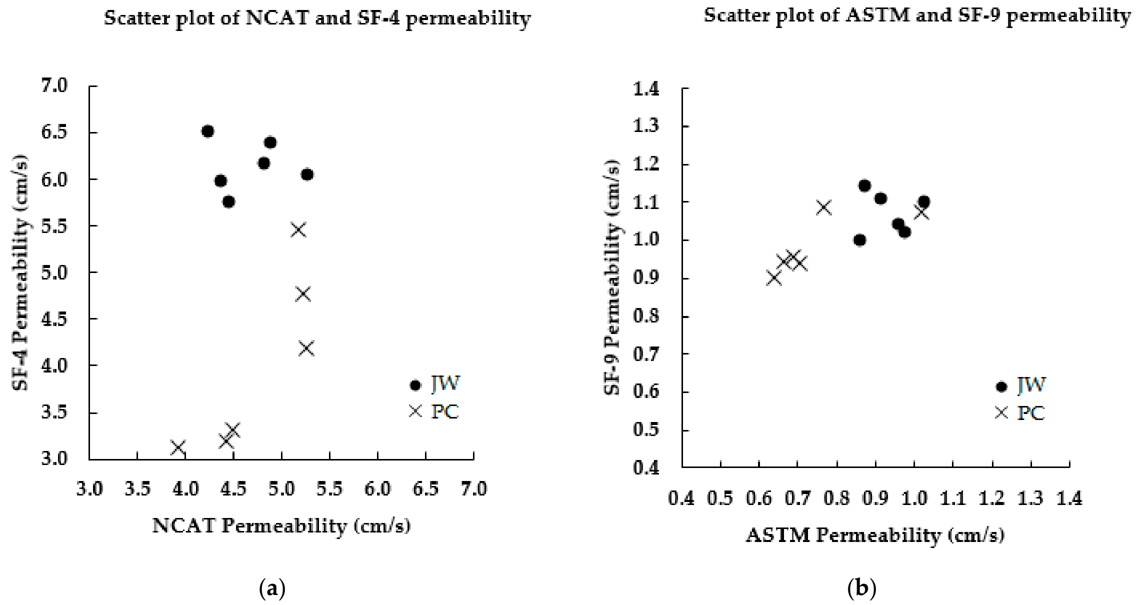


Figure 10. Scatter plots of permeability obtained by (**a**) NCAT and SF-4 methods, and by (**b**) ASTM and SF-9 methods on the north and south test locations on the JW and PC pavements.

As for the comparison between the permeability measured with different methods on PC pavement, there was no notable difference in the range of the data between the SF-4 and NCAT methods, but the permeability measured by SF-4 was lower than that by NCAT, especially for the appearance of noticeable lower permeability on few locations. As for the comparison of permeability measured with SF-9 and ASTM, the permeability measured with SF-9 was, in general, higher than that with the ASTM method. It was also found that the difference between SF-9 and ASTM in permeability was smaller than that between the SF-4 and NCAT methods.

The surface area covered using both the SF-4 and NCAT methods was the same as the test area for the JW pavement and, therefore, canceled out of the calculation. As indicated previously, the shape and dimensions of the SF-4 frame exactly covered four aqueduct openings, minimizing the impervious ratio of the test area. Even though the difference between the test area covered by the SF-4 device (165.4 cm^2) and NCAT permeameter (167.5 cm^2) was small, the void ratio was higher using the SF-4 method, likely causing the 1-2 cm/s difference in permeability.

For the measurements with the SF-9 and ASTM methods on the JW pavement, the shape and dimensions of the SF-9 frame exactly fit the nine aqueduct openings, which included the minimum impervious ratios in the test area. The test area covered by SF-9 was 552.0 cm^2 (85.6 in^2), which was smaller than that of the ASTM infiltration ring, which was 760.6 cm^2 (117.9 in^2), giving a ratio of surface areas of 1:1.37 (SF-9:ASTM). Since the SF-9 device exactly covered the pattern that represented the whole pavement, no normalizing factor was applied to the calculation. As with the SF-4 and NCAT discussion above, it was possible that the number of voids included in the measurement might be causing a difference in the permeability measurements between SF-9 and ASTM. To explain, if the square SF-9 device exactly included nine aqueduct openings, but if the circular ASTM device covered fewer openings, or partially covered some openings, the permeability measurements would be different.

Regression analyses were performed between the two falling head methods, NCAT and SF-4, and between the two constant head methods, ASTM and SF-9. The mean permeability value from each test location was used. Since a permeability of zero with one measurement should also be zero with all other measurements, the linear regression without a constant was applied to this analysis, with a confidence interval of 95%. The results of the linear regression model are shown in Table 2. Strong correlations exist, regardless of the pavement type, ranging from 0.952 to 0.994.

Table 2. Correlation between the permeability measurements obtained with different methods.

Methods Compared	Pavement Type	R^2	Coefficient α *	Standard Error
NCAT vs SF-4	JW&PC	0.952	1.083	0.109
NCAT vs SF-4	JW	0.992	1.311	0.052
NCAT vs SF-4	PC	0.981	0.856	0.053
ASTM vs SF-9	JW&PC	0.990	1.209	0.053
ASTM vs SF-9	JW	0.994	1.142	0.040
ASTM vs SF-9	PC	0.985	1.298	0.071

* $Permeability_{SF\text{-}4} = \alpha Permeability_{NCAT}$; $Permeability_{SF\text{-}9} = \alpha Permeability_{ASTM}$.

Throughout this study, the falling head methods showed permeability measurements that were several times higher than the constant head methods. It was also found that, in general, the JW pavement showed higher permeability, with both the falling head and constant head methods than the PC pavement. The way that the time elapsed was calculated for falling head versus constant head was different, with the constant head (ASTM and SF-9) methods measuring the time elapsed from when water first contacted the pavement until all water has disappeared, which included the time required for water to accumulate to a certain level, and to drain out to zero. In contrast, the elapsed time for the falling head (NCAT and SF-4) methods measured the elapsed time according to when the water level fell between two heights.

Another key element that might have caused the measurement variability was the difference of test instrument diameter specified in each of the ASTM and NCAT methods. This is in agreement with a previous study that suggested the larger size of testing ring helped reduce the lateral flow and forced more water to a one-dimensional flow, and suggested that the ASTM permeability showed a smaller value with a wider diameter of infiltration ring, compared to a higher value of NCAT with a narrower diameter of permeameter [50]. Nonetheless, an interesting observation was made on the JW pavement. As mentioned in the method section, the concrete part of JW Eco-technology was the same mixture as that used to install the impervious concrete slab. The permeability of the impervious concrete pad, as it should be, was negligible with all methods used. This indicates that on the JW Eco-technology pavement, the infiltration was in only one direction and there was no lateral flow. Thus, the permeability obtained with the JW pavement was not exaggerated by lateral flow and it should conservatively represent its capacity of allowing water flow in one dimension to the subsurface layers. Still, the results drawn from the observation of the JW Eco-technology showed pronounced differences among data collected, implying that the lateral flow might not be the primary contributor to the measurement variability in this study.

In this study, all measurements were collected by one individual. The water supply for the NCAT and SF-4 methods was from an on-site storage tank, and water outflow was controlled by a valve. It was noticed that the rate at which the instrument was filled with water to the starting head was not the same for all test locations, which likely caused slight variations in the measurements. In addition, plumber's putty was suggested in the NCAT method as the sealing agent to seal the gap between the instrument and the pavement surface. As time elapsed, the putty lost its sealing capacity and more putty was needed. As a result, it was time-consuming and required more plumber's putty than expected. It is suggested that other sealing agents should be considered, as was also suggested by Li et al. for better sealing [50].

The finding that the permeability measurements obtained using the falling head method were higher than those obtained by the constant head method in this study is in agreement with several studies performed by other research groups [50,51,64]. It may be fundamentally due to the difference in the principles of falling head and constant head. Li et al. [50] stated that the development of the NCAT permeameter was based on the theory derived from Darcy's law. On the contrary, there was no specific theory or explanation for the derivation of the equation used in the ASTM standards. Based on the formula of Equation (3), it was the mass of the specified amount of water converted to a specified depth over the time elapsed for water to infiltrate into the pavement surface [64], but how the constant K in Equation (3) was derived was not explained. The biggest reason for the difference between the constant head and falling head methods, though, may likely be due to the incorporation of the pavement thickness into the falling head calculation. The falling head method calculates a saturated hydraulic conductivity [50] that assumes that the water is not free-flowing into the pavement, which then necessitates the need to know the thickness of the pavement layer. In the case of this study, however, the pavement was not saturated, and water was free-flowing. Therefore, the use of the full pavement thickness in the calculation may be skewing the measurement. Table 1 highlights the ratio of the falling head to the constant head measurements. Future investigation may help to determine the appropriate pavement thickness for the NCAT calculations.

5. Conclusions

This study tested different methods of measuring the permeability of pavement systems, including the JW Eco-technology system, which has previously never been tested in the US. The data showed that the JW Eco-technology system and the pervious concrete had comparable permeabilities. In addition, for each test location of each pavement system, the permeability obtained by the NCAT method was approximately 4.99 and 6.36 times higher than that by ASTM standard on JW and PC pavements, respectively. The permeability measurements obtained from the SF-4 method also displayed the same trend, compared those obtained by the SF-9 method. The permeability obtained by the SF-4 method was approximately 5.74 and 4.08 times higher than that by SF-9 method on JW and PC pavements, respectively. Regression analyses suggested a strong positive correlation between the permeability measurements obtained with the SF-4 method and NCAT method, and a strong correlation between the permeability measurements obtained with the SF-9 and the two ASTM standards. These findings suggest that the shape of the device was not a factor that influenced the permeability measurements. The use of a square frame for permeability allows researchers to select a testing device to fit the specific pattern and design of a pavement system. The two different square frames used in this study showed their versatility to be effectively used for permeability measurement in JW Eco-technology, as well as the pervious concrete pavement site. Based on the results of this study, it is suggested that the ASTM method should be considered for future comparisons of permeable pavement systems. Also, as the SF-9 method showed a strong correlation with the ASTM method, it may serve as a viable option to measure the permeability of pavements with gridded openings, such as the JW Eco-technology system. Lastly, the JW Eco-technology system achieved permeability measurements that were comparable to common pervious concretes, demonstrating its potential as an alternative to current permeable pavements.

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