STRUCTURAL AND HYDROLOGICAL DESIGN OF PERMEABLE PAVEMENTS

David K. Hein, P.Eng.
Vice-President, Transportation
dhein@ara.com

D.J. Swan, P.Eng. and Lori Schaus, P.Eng.
Senior Engineer and Project Engineer
djswan@ara.com and lshcaus@ara.com

Applied Research Associates Inc.
5401 Eglinton Avenue West, Suite 105
Toronto, ON, Canada, M9C 5K6,
tel: 416-621-9555 fax: 416-621-4719

ABSTRACT

Permeable pavement technologies are an important aspect in sustainable design. Environmental responsibility through green initiatives is being embraced in the transportation industry from grass roots community groups to federal governments. One such tool in the sustainable infrastructure design arsenal is the use of permeable pavement systems to help mitigate storm water runoff. The ability to use the large areas occupied by pavements to improve hydrology and groundwater recharge has many potential benefits.

Traditional pavement surfaces are virtually impermeable and are used in conjunction with ditches and storm drains to channelize precipitation towards storm water management facilities. Permeable pavements provide a different approach. Rather than channelizing precipitation along the surface of the pavement, the water is allowed to infiltrate and flow through the pavement surface where it can be stored and slowly allowed to return into the local groundwater system. Permeable pavements provide runoff reduction and make a significant contribution to on-site trapping, removing and treating stormwater pollutants. National and provincial/state legislation in Canada and the U.S. and other countries regulating runoff has provided increased incentive for use of these pavements by public agencies.

This paper outlines a method to integrate hydrological and structural solutions. The hydrological analysis determines if the volume of water from rainfall events can be stored and released by the pavement structure. The structural capacity of PICP is determined using the American Association of State Highway and Transportation Officials (AASHTO) 1993 structural design equations to develop the base/subbase thickness to support the design traffic.

Key Words: permeable pavement structural design, pavement hydrological design, stormwater management, stormwater best practice

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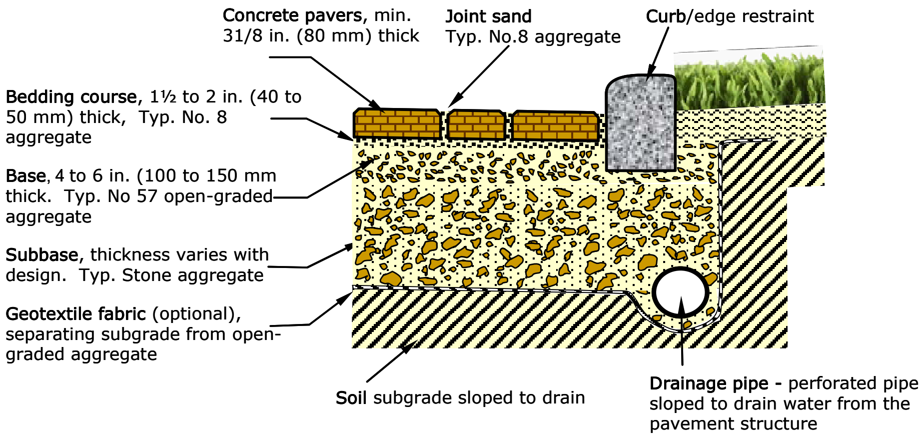
INTRODUCTION

Storm water management is a key component of urban infrastructure design. If properly designed and constructed, permeable pavements can help rainwater infiltrate soil, decrease urban heating, replenish groundwater and reduce storm water runoff. Traditional pavement surfaces are virtually impermeable and are used in conjunction with ditches and storm drains to channelize precipitation towards storm water management facilities. These facilities have a tendency to bypass natural watersheds and groundwater recharge regimes.

Permeable pavements provide a different approach. Rather than channelizing precipitation along the surface of the pavement, the water is allowed to infiltrate and flow through the pavement surface where it can be stored and slowly allowed to return into the local groundwater system. The benefits of this approach are well documented [4,2] and their use by designers is encouraged through the Leadership in Energy and Environmental Design (LEED®) Green Building Rating System™.
A typical permeable interlocking concrete pavement is shown below.

Permeable Interlocking Concrete Pavement



1.1 Selection Criteria

Permeable pavements are a good choice for recreational trails, sidewalks, parking areas and low volume roadways to assist in storm water management. Advantages of permeable pavements include:

- In perculating soils, increases infiltration
- Reduces stormwater volume/peak flows
- Reduces stormwater pollutant load
- Decreases downstream erosion

Limitations

In order to make permeable pavements, permeable, it is necessary to sacrifice some of the strength characteristics of dense graded materials used for conventional pavements. As a result, permeable pavements are typically designed for low volume traffic volumes with limited heavy vehicle loading. Vehicle loading is typically expressed in terms of the number of Equivalent Single Axle Loads (ESALs) [3] to which the pavement is exposed. Typical upper limits on ESALs are in the range of 500,000 to 1,000,000 ESALs over the design life of the pavement.

Cost Considerations

The cost of a permeable pavement section is typically higher than cost of a conventional pavement. This is primarily due to the fact that the permeable pavement is thicker to allow sufficient water storage and to provide sufficient structural capacity to accommodate vehicle loading. However, cost comparison of the entire permeable pavement system compared to a conventional pavement shows a reasonable cost comparison when taking into account the reduction or elimination of catchbasins, underground piping, drainage ditches and stormwater management ponds required for conventional designs. There are also other advantages such as reduced downstream erosion, reduced pollutant loads, less impact on existing stormwater management infrastructure, etc.

DESIGN PROCESS

The design process for permeable pavements includes consideration of structural capacity to ensure that the pavement materials and thickness is sufficient to withstand the anticipated traffic loadings and a hydrological analysis to determine if the pavement system can accommodate the water infiltration for the selected design conditions and storm event. The overall flow of the analysis can be seen in Figure 0.1 through Figure 0.3.

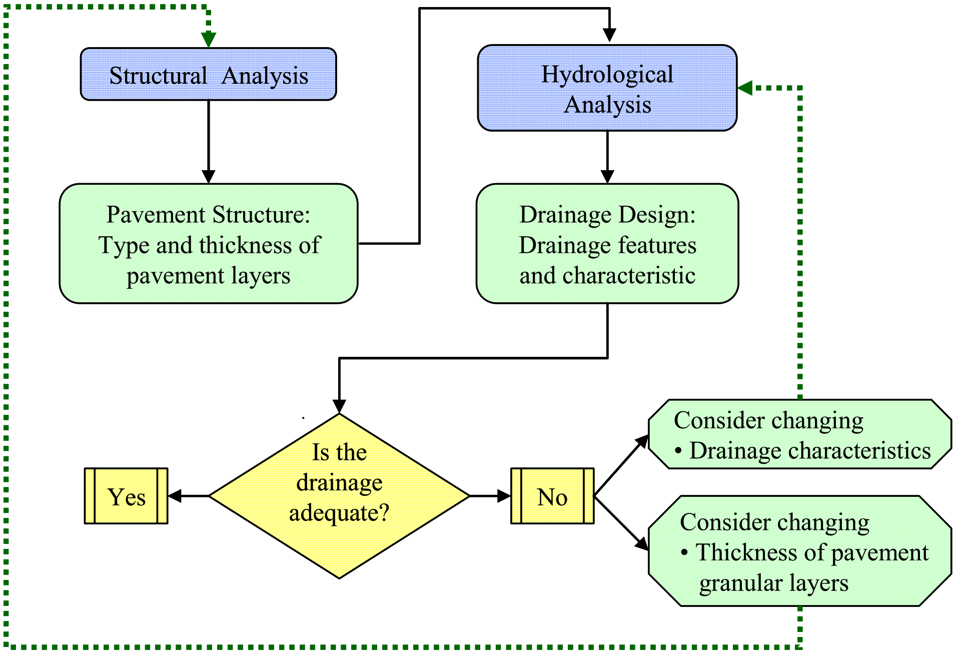


Figure 0.1 Schematic of the Analysis Process

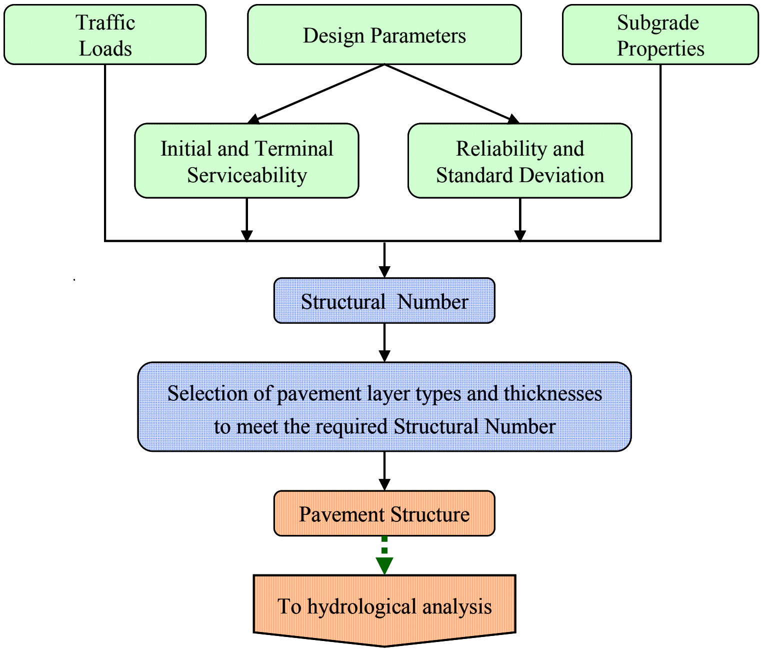


Figure 0.2 Schematic of the Structural Analysis

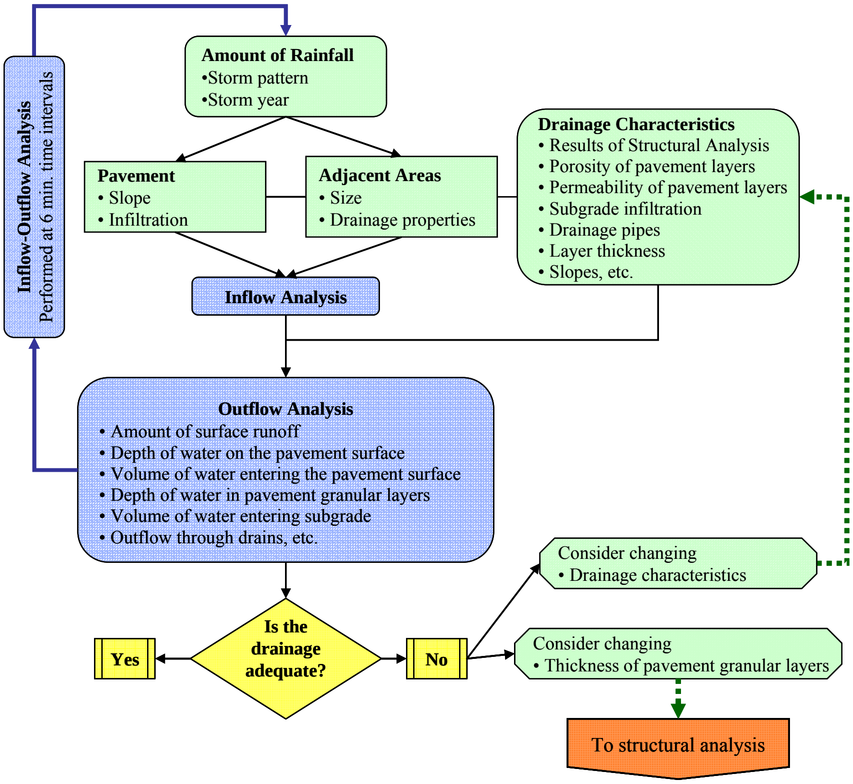


Figure 0.3 Schematic of the Hydrological Analysis

Design Inputs

Geometry

The permeable pavement geometry is needed to provide information on the configuration of the pavement structure. Specifically it is used to provide details on the dimensions of the pavement surface, pavement slope, and neighbouring catchment areas. The pavement geometry outlines the size, shape, and behaviour of pavement surface. This information is used to help estimate the volume of rainfall as well as the amount of water storage available.

Description of Necessary Inputs and Calculations

Pavement Length:	The pavement length describes the longest dimension of the pavement surface.
Pavement Width:	The pavement width describes the shorter dimension of the pavement surface.
Contributing Area:	In some conditions, the pavement surface is selected as the low point where water is to be collected. If this is not the case and the excess surface water can flow off the pavement surface.
Pavement Slope:	The slope of the pavement describes the maximum grade of the pavement area. The slope is described in terms of the drop in elevation divided by the length of the pavement as a decimal (e.g. 4 percent grade). The slope is always provided as a positive number knowing that the water will always travel down the slope.

Subgrade Layer

The subgrade material is the soil that is present below the pavement structure. This layer is important to understand in order to ensure that the pavement structure built protects the subgrade materials from damage. The drainage is also heavily impacted by the subgrade materials because a substantial quantity of the low yield storm events are typically dissipated through the subgrade materials into groundwater recharge.

The inputs for the subgrade layer are divided into three categories based on their function in the analysis:

- Gradation
- Resilient modulus
- Porosity

The gradation of the subgrade material is used to determine various calculation parameters for the material. For subgrade materials, the information collected can be used to estimate the material's strength and its ability to drain water.

Description of Necessary Inputs and Calculations

Sieve Analysis: The *Sieve Analysis* describes the gradation of the material. It uses common, pre-defined sieve sizes and allows the user to enter the percent of material (by weight) that passes each sieve size.

Percent Fines (P_{75}): The P_{75} value is used to represent the number of fines. The P_{75} is the percentage of material (by mass) that passes the 75 μm sieve size.

Representative Particle Sizes (D_{10}, D_{30}, D_{60}): The D_{10}, D_{30}, and D_{60} values represent the diameter of the particles that represent the 10, 30, and 60 percent material passing levels. These diameters are determined based on an interpolation of the particle distribution.

Coefficient of Uniformity (C_U): The *Coefficient of Uniformity* is a calculated value often used to help describe the overall distribution of particles within a material. The unit less C_U value is larger when there is a larger range of particle sizes in the material.

$$C_U = \frac{D_{60}}{D_{10}}$$

Coefficient of Curvature (C_C): The *Coefficient of Curvature* is a calculated value often used to help describe the overall distribution of particles within a material. The unitless C_C value is typically between 1.0 and 3.0 for well graded material.

$$C_C = \frac{(D_{30})^2}{D_{60} \cdot D_{10}}$$

Resilient Modulus

The subgrade material is important to understand because it often has the most variability. Since it is native material and, realistically, the only material that cannot be modified, the thickness of the other materials are designed around the subgrade strength.

In order to evaluate the subgrade strength, a geotechnical parameter known as the resilient modulus is used. The resilient modulus can be measured in the laboratory, in the field, or estimated by other methods. The resilient modulus can be measured through a variety of in-situ field measurements or in a laboratory setting. The typical values for the resilient modulus are based on historic testing and common soil classification categories. There are also correlations to the resilient modulus from other common subgrade strength indices such as the California Bearing Ratio (CBR) and the R-Value.

Description of Necessary Inputs and Calculations

Resilient Modulus (M_R): The resilient modulus value represents the strength of the subgrade soil and its resistance to traffic loading.

California Bearing Ratio (CBR): A common measure of subgrade strength used by some agencies. The correlation below allows the calculation of the resilient modulus in psi.

$$M_R = 2555\,(CBR)^{0.64}$$

R-Value (R): A measure of subgrade strength used by agencies in the southwest. The correlation below allows the calculation of the resilient modulus in psi.

$$M_R = 1155 + 555\,(R)$$

Porosity

The porosity of a granular material represents the amount of voids in any volume of the material. Information on the density of the compacted material including the voids and the density of the granular particles are used to calculate the proportion of the volume available to store water. The porosity information is also used to estimate the speed that water can move through the granular material.

Description of Necessary Inputs and Calculations

Dry Unit Weight (γ_D): The *Unit Weight* represents the bulk density of the granular material. This value is determined in a lab as the mass of the material over the compacted volume (including air voids). Most mineral soils have dry unit weights between 1,500 and 2,000 kg/m^3.

Aggregate Specific Gravity (G_S): The G_S value is the density of the aggregate particles relative to the density of water. The particle density is the mass of the particles without considering the volume of the voids between the particles. These values are a unit less ratio.

Unit Weight of Water (γ_W): The *Unit Weight of Water* is a constant value that represents the density of water at standard temperature and pressure. This value is 1,000 kg/m^3.

Porosity (n): The *n* value is the calculated percentage of the material volume that is comprised as the voids between aggregate particles.

$$n = 1 - \frac{\gamma_D}{(\gamma_W \cdot G_S)}$$

Subgrade Infiltration Reduction Factor: The subgrade Infiltration Reduction Factor is a number between 0 and 1 that indicates the factor of safety to be used on the subgrade permeability. A value of 0.5 is recommended to account for a reduction in capacity due to clogging.

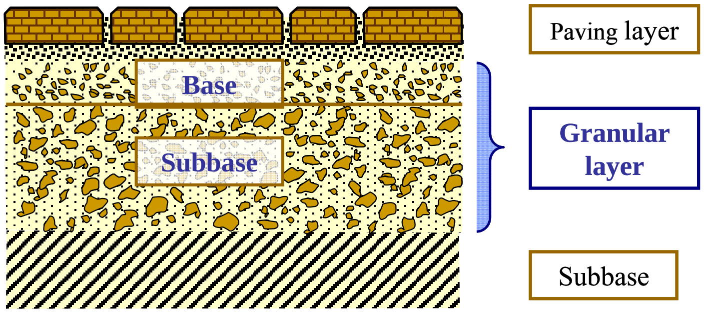
Permeability (k): The *Coefficient of Permeability* is a calculated value that represents the speed at which water travels through a granular material when subjected to a drop in pressure equal to the distance being travelled. The permeability is a calculated values based on the grain size distribution and the porosity [2]. The permeability is measured in m/day, m/s, etc.

$$k = \frac{1.894 \cdot 10^5 \cdot (D_{10})^{1.478} \cdot (n)^{6.654}}{(P_{200})^{0.597}} \qquad \text{(all values in SI)}$$

Granular Layer

The granular layers are the placed layers that are constructed above the subgrade material in order to provide structural strength and a smooth construction platform for the PICP. In permeable pavement systems, these layers are typically composed of granular materials that provide high levels of porosity to accept, store, and transport water to any outlets.

The placed granular layers are typically composed of one or two layers of aggregates known as base and subbase. In a two layer system, a subbase is place below the base to provide a low coast material that will contain most of the water in the system, while the base provides additional structural strength to prevent deformation at the surface of the subbase. In a one layer system, the material is just referred to as the base and it provides the structural support and water storage.



Description of Necessary Inputs and Calculations

Base: The base layer is a mandatory pavement layer used to store water and provide structural protection to all layers beneath it.

Subbase: The subbase layer is an optional granular layer placed below the base that is used to store most of the water and provide structural protection for the subgrade.

Base Layer Thickness: When only a single layer is used, the structural analysis is used to estimate the required thickness of the base layer. However, when two layers are selected, the distribution of the two materials needs to be specified by assign a thickness of the base layer. The remainder of the required structural capacity, if any, will be determined as the thickness of subbase by the structural analysis. Typically a base layer of 100 mm is used in a multi layer system.

Granular Layer Gradation

The gradation of the base or subbase layer is handled in a similar manner as the subgrade and base. The material gradation is a common test performed on granular material that will provide insight into many aspects of the in-situ materials performance. The sieve analysis is used to estimate the voids and the hydraulic conductivity of the base and subbase material.

Description of Necessary Inputs and Calculations

Sieve Analysis: The *Sieve Analysis* consists of a table that describes the gradation of the material. It uses the common, pre-defined sieves and allows the user to enter the percent of material (by weight) that passes each sieve.

Percent Fines (P_{75}): The P_{75} value is used to represent the number of fines. The P_{75} is the percentage of material (by mass) that passes the 75 µm sieve size. If it is not a specific value entered in the distribution, it is interpolated based on surrounding values.

Representative Particle Sizes (D_{10}, D_{30}, D_{60}): The D_{10}, D_{30}, and D_{60} values represent the diameter of the particles that represent the 10, 30, and 60 percent material passing levels. These diameters (in inches) are determined based on an interpolation within the particle distribution.

Coefficient of Uniformity (C_U): The *Coefficient of Uniformity* is a calculated value often used to help describe the overall distribution of particles within a material. The unit less C_U value is larger when there is a larger range of particle sizes in the material.

$$C_U = \frac{D_{60}}{D_{10}}$$

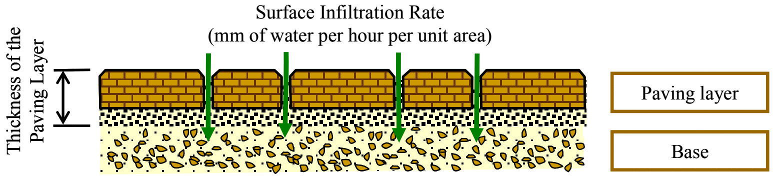
Coefficient of Curvature (C_C): The *Coefficient of Curvature* is a calculated value often used to help describe the overall distribution of particles within a material. The unitless C_C value is typically between 1.0 and 3.0 for well graded material.

$$C_C = \frac{(D_{30})^2}{D_{60} \cdot D_{10}}$$

Structural Layer Co-efficient: The structural layer co-efficient represents the relative strength of a material in terms of the Structural Number (SN) used on the 1993 AASHTO pavement design procedure [3]. A typical structural layer coefficient for a base material varies between 0.06 and 0.14 SN. A typically structural layer coefficient for a subbase material varies between 0.06 and 0.10 SN.

Paving Layer

The paving layer represents the layer of the bedding material (typically stone chip) and the pavers. This layer provides a safe and durable surface for the traffic to drive on. The stiff surface and firm support of the bedding material helps to properly distribute the traffic loads over the granular materials.



Description of Necessary Inputs and Calculations

Paving Layer Thickness: The thickness of the paving layer incorporates the depth of the paving blocks and the bedding material. The paving layer thickness is typically 130 mm, representing an 80 mm paving block and a 50 mm layer of bedding material.

Structural Layer Co-efficient: The structural layer co-efficient represents the relative strength of a material in terms of the Structural Number (SN) used on the 1993 AASHTO pavement design procedure. A typical structural layer coefficient for the paving layer is 0.30 SN.

Paving Layer Structural Number: The pavement layer SN represents the structural capacity provided by the surface layers. The paving layer SN is calculated as the product of the ***paving layer thickness*** and the ***structural layer co-efficient***. This value is used, with the required structural number, to design the thickness of the granular material.

Structural Design

The structural design is very important in the design of pavement structures. Providing the correct layer thickness will ensure that lower layers are adequately protected which will ensure a long lasting pavement. The design procedure used is consistent with the flexible pavement design procedure outline in the 1993 AASHTO Guide for the Design of Pavement Structures [3]. The structural design is based on several important parameters including the placed materials, the expected traffic loading, the minimum acceptable level of serviceability, and the thickness of the placed layers.

Traffic

The traffic loading is a critical component of the structural design. This represents the types of loads that the pavement is expected to endure and support over its service life. The traffic information used as an input to the design procedure in terms of the Equivalent Single Axle Loads (ESALs) that the pavement is able to carry during its design life. The number of ESALs represents the damage caused by an equivalent number of 80 KN axles driving on the pavement.

To estimate the total number of ESALs expected over the life of the pavement, the number and types of vehicles driving on the road need to be examined. The types of vehicle driving on the road have different characteristics, number of axles, and typical vehicle weights.

Description of Necessary Inputs and Calculations

Design Life: The design life represents the number of years that the road is being designed to last prior to reaching the minimum acceptable serviceability.

AADT: The Average Annual Daily Traffic (AADT) represents the average number of vehicles (over the entire year) that will drive, in all lanes, of the roadway.

Directional Distribution: The directional distribution represents the maximum percentage of commercial vehicles that will be travelling in either direction. Typically it is assumed that traffic is equal in both directions and the direction distribution is set to 50 percent.

Lane Distribution: The lane distribution represents the maximum percentage of commercial vehicles travelling in a single lane in each direction. If there is only one lane in each direction, this is set to equal 100 percent.

Commercial Vehicles: The proportion of the traffic that is composed of commercial vehicles greatly impacts the calculated number of ESALs. Since commercial vehicles usually have substantially higher vehicle weights, they represent the majority of the structural loading of the pavement.

Vehicle Equivalency Factor: The equivalency factor represents the average number of ESALs per commercial vehicle driving on the roadway. This value is dependent on the types of commercial vehicles on the roadways.

Traffic Growth: The traffic growth represents the annual increase in traffic expected over the service life of the pavement. The growth rate, as a percent, is used to estimate the traffic volume over the entire service life of the pavement.

Traffic Days: The traffic days represents the number of days in a year that commercial vehicles are expected to use the roadway. In most cases, it is conservative to assume that the commercial vehicles are active on weekends and holidays, such that there are 365 traffic days per year.

ESALs: The Equivalent Single Axle Loads (ESALs) is a calculated value based on the other traffic parameters. The ESALs may be entered manually, but the value will be recalculated is any of the other parameters are modified. The estimated number of annual ESALs is calculated as the product of the AADT, directional distribution, lane distribution, traffic days, commercial vehicles, and equivalency factor. The number ESALs for PICP pavement systems is typically deigned to be under about 600,000 for the expected service life.

Design Parameters

The structural design procedure for pavements has many variables. The design parameters are used to describe the condition of the roadway over the life of the pavement. The design parameters are divided into two main components representing the acceptable level of serviceability and the reliability of the design.

Description of Necessary Inputs and Calculations

Initial Serviceability: The initial serviceability (PSI_0), in terms of the Pavement Serviceability Index (PSI) represents a value from 0 to 5 as to the quality of the pavement surface. Typical values range from 4.0 to 4.5, where high PSI_0 represents a higher quality pavement surface immediately after construction.

Terminal Serviceability: The terminal serviceability, also in terms of PSI, represents the minimum acceptable level of serviceability acceptable to the travelling public. This value is dependent on the type, speed, and volume of traffic that the road is expected to support. Typical values range from 2.0 to 3.0.

Reliability: The reliability is used as a design tool to strengthen a pavement to provide the designer with a level of confidence that the service life will be reached without deteriorating below the minimum acceptable level. The reliability value is provided in terms of percent reliability. A reliability of 50 percent represents the average expected performance, while 90 percent reliability indicates that there is a 90 percent probability that the road will exceed the expected design service life.

Standard Error: The standard error (S_0) represents the expected variability in performance and the confidence in the future traffic estimates. The standard error, represents 1 standard deviation of the SN range that can reach the same cumulative traffic level. Typical values range from 0.35 to 0.45, depending on the confidence in traffic predictions.

Structural Base Thickness

The structural base thickness calculation summarizes the structural components and produces the recommended thickness of the granular materials to provide adequate structural capacity for the pavement.

Description of Necessary Inputs and Calculations

Required Structural Number (SN): The required structural number (SN) is the design value that is determined based on the design traffic, reliability, standard error, initial and terminal serviceability levels and the type and quality of the subgrade.

Paving Layer Structural Number (SN): The paving layer (SN) is the structural capacity provided by the paving layer, which includes the concrete pavers, bedding material and any base/subbase materials. The SN is calculated as the sum of the product of the pavement layer structural coefficient and pavement paving layer thickness.

Base Layer Structural Number (SN): The paving layer (SN) is the structural capacity provided by the granular base material. The SN is calculated as the product of the base layer structural layer coefficient and the base layer thickness.

Subbase Layer Structural Number (SN): *Optional* - The paving layer (SN) is the structural capacity provided by the granular subbase material, if two granular layers are present.

The SN is calculated as the product of the base layer structural coefficient and the base layer thickness.

Paving Layer Thickness: The paving layer thickness is the specified thickness of the concrete pavers and bedding material.

Base Layer Thickness: If two granular layers are specified, then the base layer thickness was provided by the user. Typically, a minimum base layer thickness of 4 inches is selected. If only one placed granular layer exists, the base layer thickness is the required thickness to meet the minimum structural capacity.

Subbase Layer Thickness: *Optional* **-** The subbase layer thickness is only present if two placed granular layers were specified. The subbase thickness is the required thickness to meet the minimum structural capacity.

Precipitation

For the safety reasons, it is very important to prevent standing water on the surface of the pavement. Standing water can cause hydroplaning of vehicles, inconvenience for pedestrians, and potential flooding of neighbouring areas.

Thus, the expected precipitation is a critical factor when designing a permeable pavement system. The pavement system must be designed to allow as much of the overland flow into the system as possible. The pavement must then store and discharge the water into the groundwater and/or storm drain system.

Storm Pattern

The storm pattern represents the change in rainfall throughout a storm event. The different types of storms represent whether the rain falls relatively evenly over a 24 hour period or if the majority of the rain occurs over a short duration. In North America, storms are typically classified as one of 4 storm patterns. The type of storm is very dependent on the location of rainfall.

Description of Necessary Inputs and Calculations

Location: The location identifies the closest city to site of the permeable pavement. The location is used to identify the storm pattern as well as typical rainfall magnitudes for a range of storm events.

Selected Storm Pattern: The storm pattern represents how much rain falls throughout a storm event. The storm pattern information for the U.S. is based on information provided by the US National Oceanic and Atmospheric Administration (NOAA).

Rainfall

The rainfall intensity is very dependent on the location of the site. The rainfall intensity is also typically provided for a range of storm events. The storm events represent the maximum rainfall expected over a 24 hour time period over a certain time period. For example, a 100 year storm represents the maximum rainfall intensity anticipated for any 1 day storm every 100 years. The longer the time period, the more extreme the storm is expected to be.

Description of Necessary Inputs and Calculations

24 Hour Rainfall: Typical rainfall intensities are available for a variety of cities across North America.

Cumulative Rainfall Distribution: The cumulative rainfall distribution graph seen below the rainfall intensity table shows the quantity of water that falls over the 24 hour time period. Selecting different lines in the rainfall chart will display the rainfall distribution for the different year storms.

Inflow

Inflow summarizes the expected flow of water into the pavement system. The inflow is composed of rainfall onto the pavement surface as well as onto any previously specified catchment areas. This rate is then used to estimate how much water will accumulate in the base material as well as how long it will take to drain a fully saturated pavement section.

Analysis Inputs

The analysis inputs all for a variety of other circumstances that are regularly found in typical PICP structures. These analysis inputs include setting initial water levels and specifying any pipe drainage systems that might be in place.

Description of Necessary Inputs and Calculations

Initial Depth of Water: Some pavement systems are prone to having water in the granular layer prior to storm events. This option allows the user to specify how much water, if any, is present in the system prior to any of the storm events.

Maximum Allowable Water Depth: This is the target water level that is not to be exceeded in a successful design. In many situations, the pavement surface (100 percent) will be the goal. However, conservative goals such as 85 percent can be used to ensure the system will not over flow.

Distance to Pipes: The maximum distance that water will have to flow to a pipe. This value is typically calculated as half the distance between two adjacent pipes.

Area per Pipe: The area per pipe represents the area of the pavement surface that is drained per individual pipe. This is necessary to determine the volume of pavement that will drain through each pipe.

Pipe Diameter: This is the inside diameter of the drainage pipes. This is used to estimate the cross-sectional area and the capacity of water that can flow through the pipe.

Distance from the Pipe to the Bottom of the Base: In many scenarios, the drainage pipes are not placed at the bottom of the pavement structure. By placing them higher in the pavement system, it encourages lower level storms to drain through groundwater recharge rather than the other storm water systems. This is the distance from the bottom of the base to the pipe perforations.

Slope: This is the slope of the drainage pipe. It is used to determine how much water can flow through the pipes.

Pipe Roughness Coefficient: The Manning's coefficient of pipe roughness is used to determine how much water can flow through the pipes.

STRUCTURAL AND HYDROLOGICAL ANALYSIS

The design of porous pavements can be somewhat complicated due to the interaction of the hydrologic properties and the structural properties of the pavement structure. The many properties of the layers, the materials, and the site layout can dramatically change the design life of a pavement.

The analysis to design the necessary pavement structure is divided into the two main components:

- Structural analysis
- Hydrological analysis

Structural Analysis

The key component of the structural design of a pavement is to ensure that the pavement surface reduces the stresses and strain at subsequent layers to prevent any significant plastic deformations. The structural analysis procedure accounts for the traffic loads and the structural capacity of the various layers in the pavement system. The structural design uses the method described in the AASHTO 1993 Guide for the Design of Pavement Structures [3].

Design Structural Number

To assess the structural capacity of a pavement, the procedure uses traffic information, material information, reliability, and serviceability levels. The design inputs are used to produce a required Structural Number (SN) for a given structure. The SN is obtained using the equation below [3]:

$$\log_{10} W_{18} = z_R * s_0 + 9.36 * \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10} M_R - 8.07$$

SN:	Structural Number representing the minimum structure needed to support the traffic loads.
W_{18}:	The traffic volume in terms of 80 kN equivalent single axle loads.
z_R:	The normal distribution statistic for the requested reliability (ie. z_R = -1.96 for 95% reliability).
s_0:	The standard error represents the variability in the traffic that the section will support due to variability in materials and construction.
ΔPSI:	The acceptable change in serviceability change from the initial construction until significant rehabilitation or maintenance.
M_R:	The resilient modulus is a measure of the stiffness of the subgrade soils. For the above equation, the M_R must be in U.S. customary units, i.e. pounds per square inch.

Design Layer Thickness

To determine the thickness of the required layers, the various placed materials are assessed and totalled to determine if they meet the design structural number. The SN is determined from the layers as:

$SN = a_1D_1 + a_2D_2 + a_3D_3$

SN: Structural number determined from the layer information. To meet the design, the layers must produce an SN equal to or greater than the design structural number. The SN is calculated as the sum of the layer thickness and structural layer coefficient products.

a: The ‘a’ values represent structural layer coefficients that are dependent on the materials being placed. The multiple ‘a’ values represent the multiple placed layers (ie. paving layer, base, and subbase).

D: The thickness of the layers. The multiple thickness values represent the multiple placed layers.

To prevent over designing the structure, the SN is set to be equal to the design structural number. For the design of porous pavements, the structural layer coefficients have been specified by the user. Since the layer thickness for the paving layer is specified, only the granular material requires a thickness. The thickness of the granular material is then rounded up to the nearest inch to ensure a reasonable and conservative value for constructability.

Hydrological Analysis

The hydrological analysis is used to assess if the rainfall can be stored and released by the pavement structure provided.

Water Balance

The quantity of water in the pavement system is described as a water balance. The volume of water in the pavement system is managed as:

$$Water\ Volume(Time) = Initial\ Water\ Level + \int_{o}^{Time} Inflow(Time) - Outflow(Time)$$

The analysis procedure uses small time steps to estimate the expected water inflow from direct precipitation and the catchment areas. The outflow in terms of runoff, groundwater recharge, and stormwater drainage during each time step is also estimated. The combined process allows the water level in the pavement system to be estimated during the storm and while draining after the rainfall has stopped.

Curve Number

The Curve Number (CN) is a common method to determine how much water in a precipitation event will runoff the surface and how much will be absorbed into the subsurface. The curve number can be estimated through either a description of the surface and published charts or through a calculation based on site specific conditions.

The curve number for adjacent sections were entered by the user or selected from standard values. The CN for the PICP system however is calculated based on the site conditions [6]:

$$CN = \frac{25{,}400}{(S+254)} \text{ - SI Units or } CN = \frac{1000}{(S+10)} \text{ - US Customary}$$

CN: Curve Number

S: Storage capacity of pavement, estimated as the storage capacity of the base and subbase thickness in millimetres or inches.

Water Inflow

The water entering the pavement comes from either precipitation or from the contributing area. During various storm events, water will fall onto the pavement surface, and adjacent catchment areas.

The water landing on the pavement will then be either absorbed into the granular material of the structure or run off the surface of the pavement. The water from adjacent catchment areas will behave in similar manner with water returning to the groundwater or running off the catchment area and onto the pavement surface. The following equation is used to estimate runoff [6]:

$$Q = \frac{\left(P - 0.2 \cdot \left(\frac{100}{CN} - 10\right)\right)^2}{\left(P - 0.8 \cdot \left(\frac{100}{CN} - 10\right)\right)}$$

Q: Direct Runoff (in)
P: Rainfall (in)
CN: Curve Number

The calculation of the runoff allows the inflow onto the surface of the pavement to be estimated. The total runoff onto the pavement surface is calculated as the sum of the runoff from all adjacent catchment areas. The runoff calculation above is then used to estimate the percentage of water at the surface of the pavement that filters into the granular materials.

In addition to the formula above which is based on the storage capacity of the pavement system, research by Borgwardt [7] has indicated that there is also a maximum rate of flow of water through the surface joints into the pavement system. Over time, depending on site conditions, the surface joints and granular material can become clogged and reduce this surface inflow by up to 85 percent. The maximum surface inflow rate is used in conjunction with the runoff rate to determine how much water can enter the system.

Water infiltration is calculated in a series of regular time steps where the precipitation is converted to volume of water inflow during each interval. Due to the additional distance that the water has to travel from the catchment areas to the pavement, an additional time lag is anticipated, which will affect the distribution of the water inflow. The time lag anticipated is calculated as:

$$T_t = \frac{0.007 \cdot (n \cdot L)^{0.8}}{P^{0.5} \cdot s^{0.4}}$$

T_t: Travel time (hours)
n: Manning's roughness number
L: Length of travel distance (ft)
P: Precipitation (in)
S: Slope of hydraulic grade line (%)

Water Outflow

Throughout the analysis period, water will be leaving the system as well as entering the system. The main paths for drainage include:

- Groundwater recharge
- Stormwater drainge system, i.e. piping
- Surface runoff

All of the drainage options are not necessarily available for all pavement sections. Depending on the options selected by the user in the pavement geometry and analysis settings, the water will be allowed to leave the pavement structure in any combination of ways.

Groundwater Recharge

Groundwater recharge is a constant method of drainage in pavement sections. The water is allowed to percolate through the subgrade material into the natural water table. The amount of water entering the subgrade is determined primarily by the subgrade hydraulic conductivity.

The flow rate of water is based on Darcy's Law assuming saturated conditions and gravity fed hydraulic gradient. With little information typically available regarding the exact level of the water table, the hydraulic gradient is assumed based on surface conditions.

The subgrade infiltration reduction factor is used in this calculation to account for less than saturated conditions and potential clogging due to movement of fine particles into the subgrade. The factor is expected to have a typical value of 0.5.

$$Q_{Groundwater} = k_{Subgrade} \cdot \frac{Depth\ of\ Water\ in\ Pavement}{Thickness\ of\ Pavement} \cdot Subgrade\ Infiltration\ Factor$$

$Q_{Groundwater}$: Flow rate of water into groundwater recharge (m/day)
$k_{Subgrade}$: Hydraulic conductivity of the subgrade material (m/day)

The water depth in the pavement is calculated for every time step due to the changing depth of water in the pavement materials. As the depth increases, the static pressure is expected to increase which will directly affect the rate of drainage.

Stormwater Drainage System

It is common for porous pavement systems to be connected to stormwater systems. Through the use of subsurface drains, excess water within a pavement system can be removed and drained into stormwater drains or other hydraulic features.

The stormwater systems in most traditional pavement systems have the drains at the bottom of the pavement structure to ensure that the water is removed complete from the system. However, in many cases the drains in PICP systems, are place in the middle of the section to encourage lesser storms to drain into the ground rather than into stormwater systems.

The rate of drainage into stormwater systems is limited by the rate the water can move towards the drain and the amount of water that can travel in the pipe. The flow through the granular base/subbase is determined based on a typical 2D flow net solution [8]:

$$Q_{Granular} = k_{Base/Subbase} \cdot \left(\frac{h^2}{b} \right) \cdot L$$

$Q_{Granular}$: Flow rate of water through the granular base/subbase towards the drainage pipe (m^3/day)
$k_{Base/Subbase}$: Hydraulic conductivity of the base or subbase material (m/day)
h: Height of water level above the drain (m)
b: Longest horizontal distance the water is expected to travel to reach a drain (m)
L: Length of pipe along project calculated as the pavement area divided by *b* (m)

If the base material has the ability to drain quickly, it is possible that more water will be attempting to flow through the drainage pipes than gravity will allow. This could be the limiting factor if the pipes are under designed in some of the porous materials. Manning's equation is used to estimate the amount of water flow in a pipe.

$$Q_{Pipe} = \frac{1}{n} \cdot \pi \cdot r \cdot \left(\frac{r}{2}\right)^{\frac{2}{3}} \cdot s^{\frac{1}{2}}$$

Q_{Pipe}: Maximum flow rate of water through any pipe (m^3/day)
n: Manning's roughness coefficient
p: 3.14159
r: Pipe radius (m)
s: Slope of pipe (%)

The total drainage through a stormwater system will be equivalent to the lesser of the flow through the granular material or the maximum flow rate through the pipe system.

Surface Runoff

Surface runoff is a different type of outflow in that it represents the water that cannot enter the system, rather than the removal of water already in the pavement system. In addition to the water that is not expected to absorbed into the system due to the curve number, it is also possible for the base material to be fully saturated, which will cause all additional water to be either pool on the surface or become runoff, depending on the grading of the site and adjacent drainage features.

If surface runoff is possible due to the site layout, the quantity of runoff will be equivalent to the inflow rate, after other drainage options are accounted for, while the pavement structure is filled to capacity. It is assumed the destination has sufficient capacity to accept the surface water runoff.
If the site layout does not allow for surface water runoff, it is assumed that the water will pool on the surface of the pavement. The water level on the surface will be monitored until sufficient subsurface drainage has occurred to lower the water level below the pavement surface.

ANALYSIS RESULTS

A software application called Permeable Design Pro has been designed to complete the structural and hydrological design of permeable interlocking concrete pavements. The application is available from the Interlocking Concrete Pavement Institute (ICPI) at www.icpi.org. To assist the designer in evaluating a PICP design, a variety of design details and graphics are produced. The software also provides a printable report that summarized the design inputs and the results.

Hydrology Graphs

The hydrology of the site and the accumulation of water in the system is a dynamic process throughout various storm events. Graphs are used to assist the designer in understanding water inflow and exit from the pavement system at various time intervals during and after the storm. The graphs represent:

- Precipitation – The depth of rain to fall during the given analysis interval.
- Inflow – The volume of water to enter into the pavement system during any time interval.
- Surface Runoff – The volume of water that will not enter the pavement system and drain over the surface of the pavement into a downstream field, pond, or other stormwater infrastructure.
- Surface Water Depth – The depth of standing water that has pooled on the surface of the PICP because the base and subbase materials are full saturated.

- Depth of Water in Base – The saturated water level in the base material. The shaded area at the surface of the base material indicates the water level at which the design goal has been exceeded.
- Pipe Drainage – The volume of water that is removed from the granular materials through pipe drainage.
- Deep Percolation – The volume of water that exits the pavement into the subgrade.

Summary Graph

The summary graph is used to provide an overall assessment of how the PICP system behaves for a variety of storms. The graph shows the maximum water level, at any time point, in the granular layers. If the water level fills and then exceeds the thickness of the base/subbase, the value displayed is adjusted by the porosity to indicate the thickness of base it could possibly fill. A logarithmic regression is then used to interpolate points for storms other than the standard design storm.

Equivalent design storms can also be assessed from the summary graph. These represent the frequency of a storm that would achieve a certain maximum water level. The two equivalent design storms of interest represent the frequency of storm that would meet the design goal outlined and the frequency of storm that would cause the entire pavement system to reach capacity and become fully saturated.

Detail Table

A significant number of calculations are performed depending on the time step and storm/drainage duration selected. The detailed calculation results are provided in tabular form to allow for further investigation by the designer, if desired. The information can be sorted, filtered, or copied to other software applications for analysis and reporting.

Report

The analysis report was designed to permit the designer to conveniently print and store the key inputs and the design results. The report is designed to be printed with all necessary information in an easy to read format. The report can be either printed or exported to a variety of electronic formats including Adobe PDF files and Microsoft Excel spreadsheets.

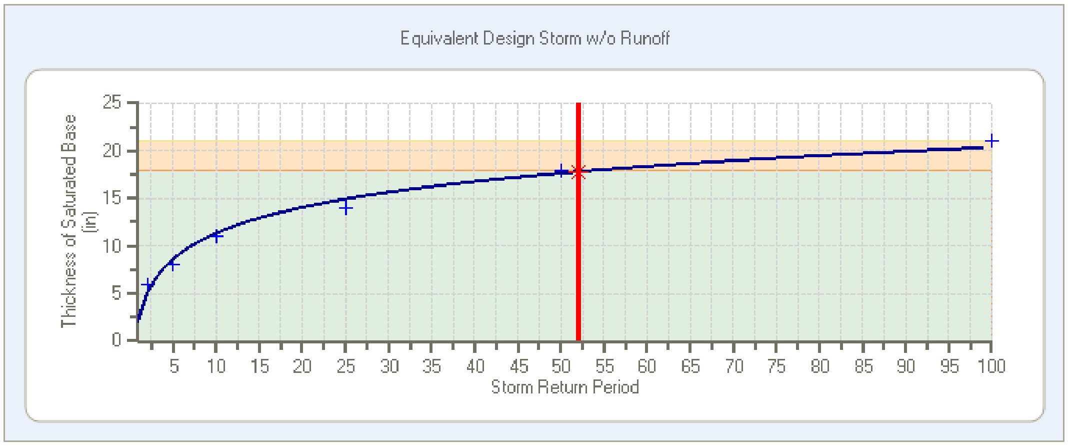
MAINTENANCE

All pavements require maintenance to ensure adequate performance. For permeable interlocking concrete pavements, this would require periodic vacuum sweeping (at least twice yearly) of the pavement surface and joints to assist in removing any fine particles that may enter the joints and reduce their permeability. Other periodic maintenance such as replacing cracked or worn pavers, minor settlement repairs, etc. would assist in extending the service life of the pavement.

EXAMPLE INTERLOCKING CONCRETE PAVEMENT DESIGN

A permeable interlocking concrete pavement design is required for a parking area at a college campus. The pavement area is 8,000 m^2. The design must be capable of accommodating a 50 year design storm without any surface water runoff. The pavement is expected to accommodate 750 vehicles a day with 5 percent heavy vehicles with a growth rate of 1 percent over a 15 year design period. The truck factor is estimated to be 1.2. The initial and terminal design serviceability values are 4.1 and 2.5 respectively with a design reliability of 80 percent and standard deviation of 0.44. The parking area is surrounded by a recreational field with a silty clay subgrade covered by grass. The maximum drainage length of the contributing area is 20,000 m^2. The subgrade under the permeable pavement is silty clay with low permeability. The unit weight of the silty clay is 1,680 kg/m^3. The subgrade is expected to become gradually clogged with fines washed in from the pavement surface over time such that it loses 25 percent of its permeability. The pavement structure is to include 80 mm pavers with a 50 mm bedding course (combined structural layer coefficient = 0.3), 100 mm thick granular base of ASTM No 57 stone (structural layer coefficient = 0.14) and granular subbase of ASTM No. 2 stone (structural layer coefficient = 0.1). The paving layer surface infiltration capability is 50 mm/hr. The thickness of the granular subbase layer is to be determined based on the thickness and hydrology design. The pavement has a 2 percent slope. There is no water assumed to be in the subbase material and the maximum depth of water allowed in the base/subbase material is 85 percent of the thickness. Given the low permeability of the subgrade layer, the pavement is to be designed to include drainage pipes to supplement water percolation into the subgrade. Water is not permitted to run off the pavement surface during any storm.

The results of the design follow. The drainage and structural design for this example are balanced. A structural number of 107 mm is required to accommodate the design traffic and with a base thickness of 100 mm and subbase thickness of 425 mm, a structural number of 109 mm is provided. The 425 mm subbase thickness is capable of accommodating a 52 year design storm as shown below.



In order to ensure that there is no surface water runoff, 105 mm diameter drainage pipes are required to drainage an area of 500 m^2 with a maximum drainage distance of 6 m between the collection pipes.

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