Structural and Hydrological Design of Sustainable Pervious Concrete Pavements

Robert Rodden, P.E., Director of Technical Services and Product Development
Gerald Voigt, P.E., President and CEO
American Concrete Pavement Association

Tim Smith, P.Eng., Senior Pavement Engineer
Stantec Consulting Ltd.

Paper prepared for presentation

at the Successes in the Pavement Industry (PS) Session

of the 2011 Annual Conference of the
Transportation Association of Canada
Edmonton, Alberta

Abstract

Building on previous advances in thickness design methodologies for jointed plain concrete pavements, a mechanistic design methodology for use in the structural design of pervious concrete pavements is presented. Although most jointed plain concrete pavement structural design methods include both fatigue (e.g., slab cracking) and erosion (e.g., faulting or surface smoothness) as failure criterion, the proposed pervious concrete pavement structural design includes fatigue as the sole failure criteria due to a lack of evidence that erosion occurs on pervious concrete pavements. To ensure both an optimal structural design and that stormwater management requirements are met, a hydrological design method that varies the subbase/reservoir layer thickness to meet hydrological demand also is presented. These structural and hydrological design methodologies have been combined into software called PerviousPave, a user-friendly tool for the design of sustainable pervious concrete pavements. Example program runs are also provided to demonstrate the ease of use of the program and how the user can design their own pervious concrete pavement.

1.0 Introduction

Pervious concrete pavement is a porous pavement, often with an underlying stone reservoir, that captures rainfall and stores runoff before it infiltrates into the subsoil. This pervious surface is a sustainable solution that replaces traditional pavement and allows stormwater to infiltrate directly into the ground, permitting a naturally occurring form of water treatment. Pervious concrete mixtures consist of specially formulated hydraulic cementitious materials, water, and uniform open-graded coarse aggregate (e.g., ASTM C33 Size Numbers 5, 56, 67, 8, and 89). When properly designed and installed, pervious concrete has a high percentage of void space (15% or more) to accommodate stormwater from significant storm events (Figure 1).

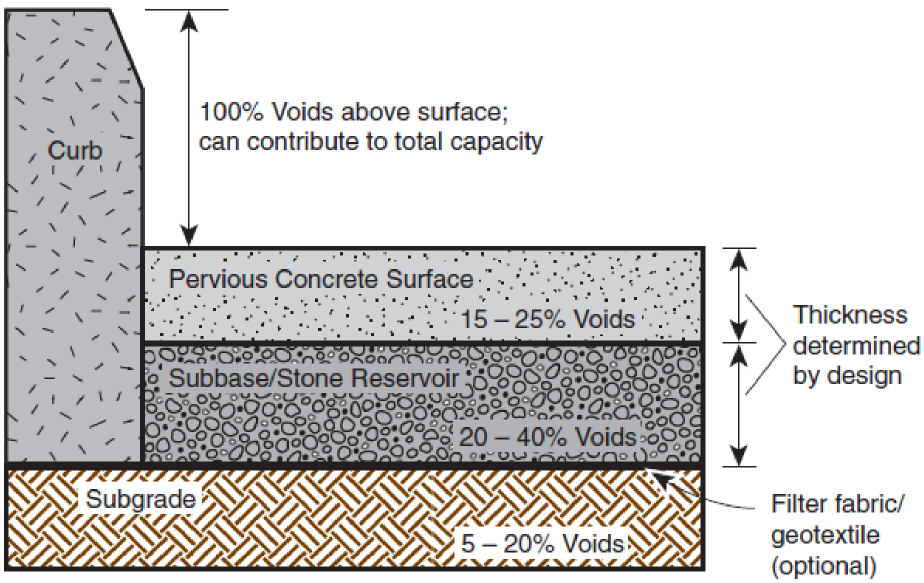

Figure 1. Typical cross-section of pervious concrete pavement [1]. On level subgrades, stormwater storage is provided in the pervious concrete surface layer (15% to 25% voids), the subbase (20% to 40% voids), and above the surface to the height of the curb (100% voids).

Pervious concrete pavement is ideal around buildings (e.g., walkways, courtyards, etc.), as parking lots (Figure 2) and as low-volume roadways. Pervious concrete pavement also has some application on highways, where it can be used in shoulder and median construction for stormwater runoff mitigation. It also may be used as a surface material to reduce hydroplaning, splash and spray, and mitigate tire-pavement noise.

Figure 2. A pervious concrete parking lot in Georgetown, Ontario [2].

2.0 Background on Concrete Pavement Thickness Design Software

The Portland Cement Association (PCA) thickness design method for jointed plain concrete pavements (JPCP), published in 1966, used slab stress/fatigue as the sole design criterion [*3*]. This design method was updated by PCA in 1984 to include consideration of edge support and pavement failure by pumping /erosion [*4*, *5*]. Another update came in 2005, when the American Concrete Pavement Association (ACPA) incorporated additional enhancements including the ability to analyze tridem axles in the traffic spectrum [*6*], recommendations for doweled joints, and an enhanced concrete fatigue model that included a reliability component [*7*]. This updated JPCP design methodology was incorporated in new ACPA software called StreetPave [*8*].

In 2010, ACPA developed an adaptation of this ever evolving design methodology in the form of a new structural and hydrological design software for pervious concrete pavements called PerviousPave [*9*]. The primary updates in the adaptation of this software were the exclusion of erosion as a failure criterion, and the inclusion of a hydrological design component. Guidance is also given on variables that differ between pervious and conventional concrete pavements, such as the maximum strength, use of dowel bars, traffic distributions, and types of reservoir layers (e.g., subgrade and subbase) that typically are used.

3.0 Pervious Pavement Design Criteria and Assumptions

3.1 Fatigue Design Criteria – Although several studies have investigated the fatigue behavior of pervious concrete [*10, 11*], the limited mixture designs and number of samples used in these studies, as well as other concerns such as fatigue of a laboratory specimens versus full-sized slabs, have prevented the widespread acceptance of any existing pervious concrete fatigue model(s). Other research has suggested that the fatigue behavior of pervious and conventional concrete is similar [*12*]. As such, and until a well-accepted fatigue equation for pervious concrete is developed, PerviousPave utilizes the enhanced concrete fatigue model that was developed during the 2005 update of StreetPave [*7*].

3.2 Hydrological Design Criteria – Many pervious concrete pavement hydrological design methodologies exist, including the Soil Conservation Service (SCS) Method [*13*], the Los Angeles County Method [*14*], the Rational Method [*15*], and many locally-tailored methods. An adaptation of the Los Angeles County Method [*14*] was chosen for inclusion in PerviousPave because it allows for a project's hydrologic requirements to be considered in conjunction with the pavement structural design.

In PerviousPave, the required concrete slab thickness determined by the structural design algorithm is used as a direct input for the hydrological design; the thickness of the reservoir layer(s) is increased, as necessary, until the pervious concrete pavement structure is capable of meeting the stormwater management requirements. Together, this method ensures that the optimal structural design and stormwater requirements are met for the project.

3.3 Design Strength Assumption – While a formal method of conducting compressive, flexural, and/or modulus testing of pervious concrete pavement specimens has not yet been published by the American Society for Testing and Materials (ASTM) or another organization, the fatigue equations used in PerviousPave assume such inputs to be comparable in nature (but not magnitude) to those used for conventional concrete pavements; this assumption will be revisited in the development of future updates to PerviousPave and as research into the topic evolves.

3.4 No Pumping/Erosion Failure Criterion – The pumping/erosion failure criterion in ACPA's StreetPave is based on studies by state highway departments and the PCA during the 1930's and 1940's. These studies identified three factors necessary for pumping to occur [*16*]:

- An erodible subbase material or a fine-grained subgrade,
- Water in the subgrade/subbase to serve as a transport medium, and
- Heavy, fast moving loads (e.g., trucks, not automobiles).

Further research determined that poor joint load transfer (e.g., undoweled joints) represents a fourth necessary factor [*17*].

Pervious concrete pavements typically are used in applications with few fast moving, heavy loads, and the reservoir layer(s) typically consist of a non-erodible material. Also, and although this has not been directly researched, the voids in pervious concrete mixtures help dissipate hydraulic pressures under vehicle loads because water trapped in the reservoir layer has ample escape paths. Because of these considerations and a lack of evidence of erosion as a failure mode for pervious concrete pavements in the field, ACPA excluded pumping/erosion as a failure criterion in PerviousPave.

3.5 No Surface Distress Failure Criterion – Although surface raveling from freeze-thaw damage and the turning motion of heavy vehicles are possible failure modes for pervious concrete pavement, acceptable models have not yet been developed to predict such failure modes. Regardless, resistance of the surface to such distresses is controlled strictly by materials and construction techniques. PerviousPave, as a structural and hydrological design software, is predicated on best practices for materials and construction. This assumption is parallel to and consistent with the omission of material-related distresses in other concrete and asphalt pavement structural design methodologies.

4.0 Structural Design

Metric Units Note: All calculations performed in PerviousPave are done in English units; when using the Metric units mode, all inputs are converted to English units before use in calculations. The software then calculates the answer in English units, converts the answer to Metric, and displays the results for the user to analyze.

The total fatigue damage (FD_{total}), with considerations of the damage caused by single, tandem, and tridem axle loads, for a JPCP such as a pervious concrete pavement can be written as:

$$FD_{total} = FD_{single} + FD_{tandem} + FD_{tridem} \quad (1)$$

where,

FD_{total} = total fatigue damage, %
FD_{single} = fatigue damage from single axle loads, %
FD_{tandem} = fatigue damage from tandem axle loads, %
FD_{tridem} = fatigue damage from tridem axle loads, %

Fatigue damage (FD) for each axle type/load group in Equation 1 can be computed using Miner's damage hypothesis [*18*]:

$$FD = \frac{n}{N_f} \quad (2)$$

where,

n = number of load applications, calculated from the project's traffic data
N_f = allowable load applications to failure

The allowable load applications to failure can be calculated as [*7*]:

$$\log N_f = \left[\frac{-SR^{-10.24} \log(1-P)}{0.0112} \right]^{0.217} \quad (3)$$

where,

SR = stress ratio
P = probability of failure, %

In PerviousPave, the probability of failure is calculated as:

$$P = 1 - R * \frac{SC}{50} \quad (4)$$

where,

R = reliability, %
SC = percent slabs cracked at the end of pavement's life (assumed as 15%), %

The stress ratio is the calculated equivalent stress divided by the strength of the concrete:

$$SR = \frac{\sigma_{eq}}{MR} \quad (5)$$

where,

σ_{eq} = equivalent stress, psi
MR = flexural strength of the concrete, psi

The equivalent stress, assumed at the slab edge, can be calculated using the following [*5*, *6*]:

$$\sigma_{eq} = \frac{6 * M_e}{h_c^{\,2}} * f_1 * f_2 * f_3 * f_4 \quad (6)$$

where,

M_e = equivalent moment, psi

$$M_e = \begin{cases} -1600 + 2525 * \log(\ell) + 24.42 * \ell + 0.204 * \ell^2 \text{(for single axles with no edge support)} \\ 3029 - 2966.8 * \log(\ell) + 133.69 * \ell - 0.0632 * \ell^2 \text{(for tandem axles with no edge support)} \\ -414.6 + 1460.2 * \log(\ell) + 18.902 * \ell - 0.1243 * \ell^2 \text{(for tridem axles with no edge support)} \\ (-970.4 + 1202.6 * \log[\ell] + 53.587 * \ell) * (0.8742 + 0.01088 * k^{0.447})\text{(for single axles with edge support)} \\ (2005.4 - 1980.9 * \log[\ell] + 99.008 * \ell) * (0.8742 + 0.01088 * k^{0.447})\text{(for tandem axles with edge support)} \\ (-88.54 + 134.0 * \log[\ell] + 0.83 * \ell) * (11.3345 + 0.2218 * k^{0.448})\text{(for tridem axles with edge support)} \end{cases} \quad (7)$$

h_c = concrete pavement thickness, in.

f_1 = adjustment factor for the effect of axle loads and contact area

$$f_1 = \begin{cases} \left(\frac{\text{SAL}}{24}\right)^{0.94} * \frac{24}{18} \text{ for single axles} \\ \left(\frac{\text{TAL}}{48}\right)^{0.94} * \frac{48}{36} \text{ for tandem axles} \\ \left(\frac{\text{TRIAL}}{72}\right)^{0.94} * \frac{72}{54} \text{ for tridem axles} \end{cases} \quad (8)$$

f_2 = adjustment factor for a slab with no concrete shoulder [*19*]

$$f_2 = \begin{cases} 0.892 + \left(\frac{h_c}{85.71}\right) - \frac{h_c^{\ 2}}{3000} \text{ for no shoulders} \\ 1 \text{ for with shoulder} \end{cases} \quad (9)$$

f_3 = adjustment factor to account for the effect of truck (wheel) placement at the slab edge (assumed as 0.894 for 6 percent trucks at the slab edge; a conservative estimate for applications such as parking lots because traffic typically is not as channelized as on concrete streets, roads, and highways)

f_4 = adjustment factor to account for approximately 23.5% increase in concrete strength with age after the 28th day and reduction of one coefficient of variation (COV) to account for materials variability

$$f_4 = \frac{1}{[1.235*(1-COV)]} \quad (10)$$

where,

l = radius of relative stiffness, in.

$$l = \sqrt[4]{\frac{E{h_c}^3}{12(1-\mu^2)k}} \quad (11)$$

E = modulus of elasiticty of the concrete, psi
k = composite modulus of subgrade/subbase reaction, pci
μ = Poission's ratio of the concrete (assumed to be 0.15)
SAL = single axle load, kips
TAL = tandem axle load, kips
TRIAL = tridem axle load, kips

PerviousPave incrementally increases the pervious concrete thickness and calculates FD_{total} for each axle type/load group until FD_{total} reaches 100%, the limiting structural design criterion.

5.0 Hydrological Design

Metric Units Note: All calculations performed in PerviousPave are done in English units; when using the Metric units mode, all inputs are converted to English units before use in calculations. The software then calculates the answer in English units, converts the answer to Metric, and displays the results for the user to analyze.

The structural design above calculates the necessary pervious concrete thickness to service the design traffic over the design life of the pavement; this required thickness is held constant during the hydrological design. To ensure stormwater requirements are met, PerviousPave increases the reservoir layer thickness, if necessary, or adds a reservoir layer if one was not already included in the structural design.

The volume of water to be drained by the pervious concrete pavement can be expressed as:

$$V = \left(A_p + A_b\right) * \frac{I}{12} \tag{12}$$

where,

V = volume of water, ft^3
A_p = pervious concrete area, ft^2
A_b = non-pervious area to be drained (e.g., roofs, hardscapes, etc.), ft^2
I = storm intensity, in.

The Los Angeles County Method's [*14*] formula for required pervious concrete area is:

$$A_p = \frac{12 * V}{r_s * h_s} \tag{13}$$

where,

r_s = void ratio of the reservoir layer, %
h_s = thickness of the reservoir layer, in.

Equation 13 assumes that the entire volume of water will be contained within and processed by the reservoir layer. If, instead, the capacity of the pervious concrete layer, the capacity of the reservoir layer, and any curb height that might contribute to the total capacity of the system (at 100% voids) are included, Equation 13 can be expressed as:

$$A_p = \frac{12*V}{h_{curb} + r_c*h_c + r_s*h_s} \quad (14)$$

where,

h_{curb} = height of curb or height of allowable ponding, in.
r_c = void ratio of pervious concrete pavement, %

From a pavement engineer's perspective, the area to be paved likely is predetermined from site design considerations (lane designs, parking lot size, etc.). With all other variables set by the user, or pre-calculated from the structural design, the thickness of the reservoir layer can be determined as:

$$h_s = \frac{1}{r_s}\left(\frac{12*V}{A_p} - h_{curb} - r_c * h_c\right) \quad (15)$$

The detention time must then be checked to ensure that the pervious concrete pavement structure will be capable of processing the total volume of water in the desired time. The Los Angeles County Method, again assuming that the reservoir layer will process the entire volume of water, suggests using this expression to solve for the reservoir layer thickness [*14*]:

$$h_s = \frac{E*t_d}{r_s} \quad (16)$$

where,

E = permeability/infiltration rate of the soil, in./hr
t_d = maximum detention time of water in pervious section (typically 24 hours or less), hr

Because the required reservoir layer thickness has been determined through Equation 15, detention time only needs to be checked rather than being used as the basis for the reservoir layer thickness determination. Because the curb section and the pervious concrete pavement surface might again be included in the total capacity, Equation 16 can be expressed in more general terms as:

$$E * t_d = h_{curb} + r_c * h_c + r_s * h_s \quad (17)$$

Combining Equations 14 and 17, the detention time of the as-designed system can be calculated as:

$$t_d = \frac{12*V}{A_p*E} \tag{18}$$

If the calculated detention time per Equation 18 is less than the maximum detention time inputted by the user, t_d^*, the reservoir layer thickness calculated by Equation 15 is sufficient. However, if the calculated detention time is greater than t_d^*, the reservoir layer thickness must be increased to satisfy the detention time requirement. By setting t_d equal to t_d^* and solving for the reservoir layer thickness in Equation 17, the required reservoir thickness can be solved for when the detention time controls the hydrological design:

$$h_s = \frac{E*t_d^* - h_{curb} - r_c* h_c}{r_s} \tag{19}$$

If the hydrological design results in a thicker reservoir layer section than was included in the structural design, the structural design will become more conservative; if this is the case, the user is notified that they might choose to re-run the structural design to determine if a thinner pervious concrete pavement section is possible.

6.0 Pervious Concrete Pavement Design Comparison

Most all pervious concrete pavement structures constructed to date have focused more on the sustainable and hydrological aspects of pervious concrete and they typically are installed on sections without fast-moving heavy traffic; thus, detailed structural calculations oftentimes are not conducted as part of the design procedures. Instead, experience typically dictates if the concrete and reservoir thicknesses required for the hydrological design seem sufficient to carry the traffic that will be applied to the pavement. There has been, however, an exceptionally well document ongoing set of pervious concrete performance research projects being conducted in Canada by Vimy Henderson and Dr. Susan Tighe [2, 20, 21] that may serve as a reasonable comparison to PerviousPave. The pervious pavements included in this research project were designed using a combination of ACPA's StreetPave for the structural design and the National Ready Mixed Concrete Association's (NRMCA's) Pervious Concrete: Hydrological Design and Resources software for the hydrological design [21].

6.1 Structural Design Comparison – To compare PerviousPave results to Dr. Tighe's research, two PerviousPave design runs were conducted, one utilizing a 200 mm granular subbase and another utilizing a 250 mm granular subbase. Inputs used in the PerviousPave structural design include:

- *Project Details:* A design life of 15 years and a reliability of 80% are assumed because such values are not reported in the referenced research (Figure 1).
- *Traffic Details:* Traffic is assumed as "Residential/Parking Lot" with an average of 2 trucks per day because the referenced research describes all sites as either a driveway or parking lot (Figure 2).
- *Pervious Concrete Properties:* The referenced research reported 28-day pervious concrete ***compressive*** strengths ranging from 11.5 to 14.4 MPa, depending on compaction method; based on common conversions [22], a conservative ***flexural*** strength of 2.0 MPa is assumed. The Modulus of Elasticity of the pervious concrete is assumed as 13,500 MPa based on a conversion built into PerviousPave (Figure 3).
- *Subgrade/Subbase Support Details:* The subgrade support is conservatively assumed to have a CBR of 2 (correlating to a Resilient Modulus of the Subgrade of 21.5 MPa) because subgrade support values are not reported in the referenced research. The pervious concrete and reservoir layer thickness for Sites 3 through 5 of the referenced research are listed in Table 1. Using the built-in composite k-value calculator in PerviousPave and assuming that the reservoir layer has a resilient modulus of 150 MPa, the composite subgrade plus subbase k-value is 53.9 MPa/m and 58.3 MPa/m with a 200 mm and 250 mm thick reservoir layer, respectively.

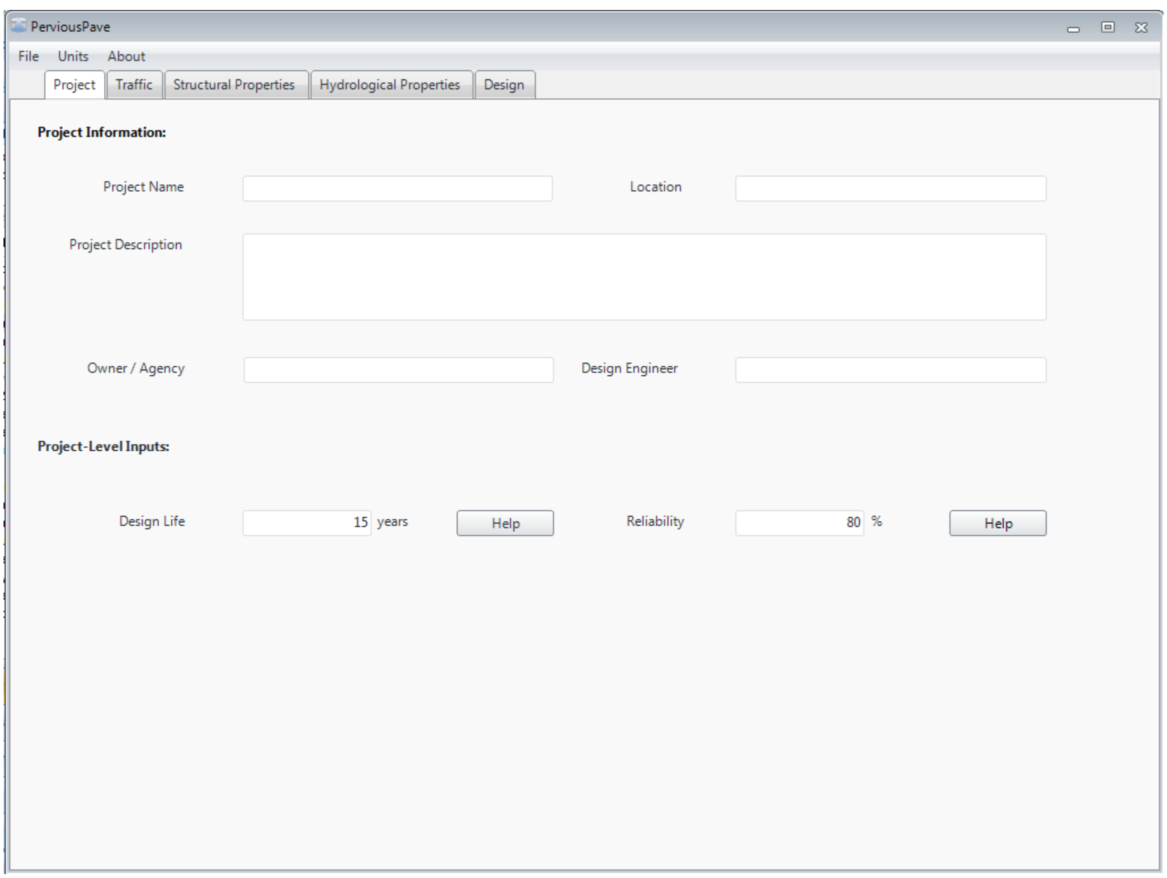

Figure 1. Project Details tab in PerviousPave.

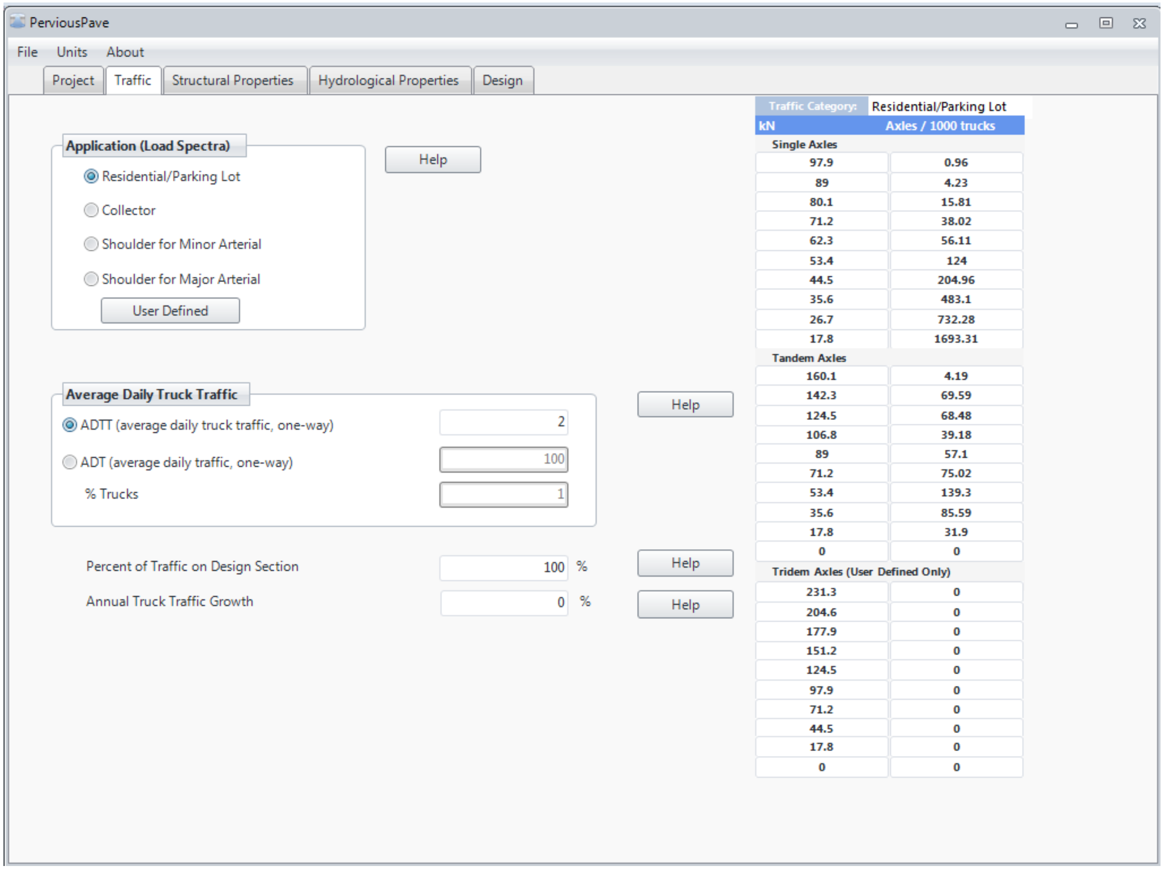

Figure 2. Traffic Details tab in PerviousPave.

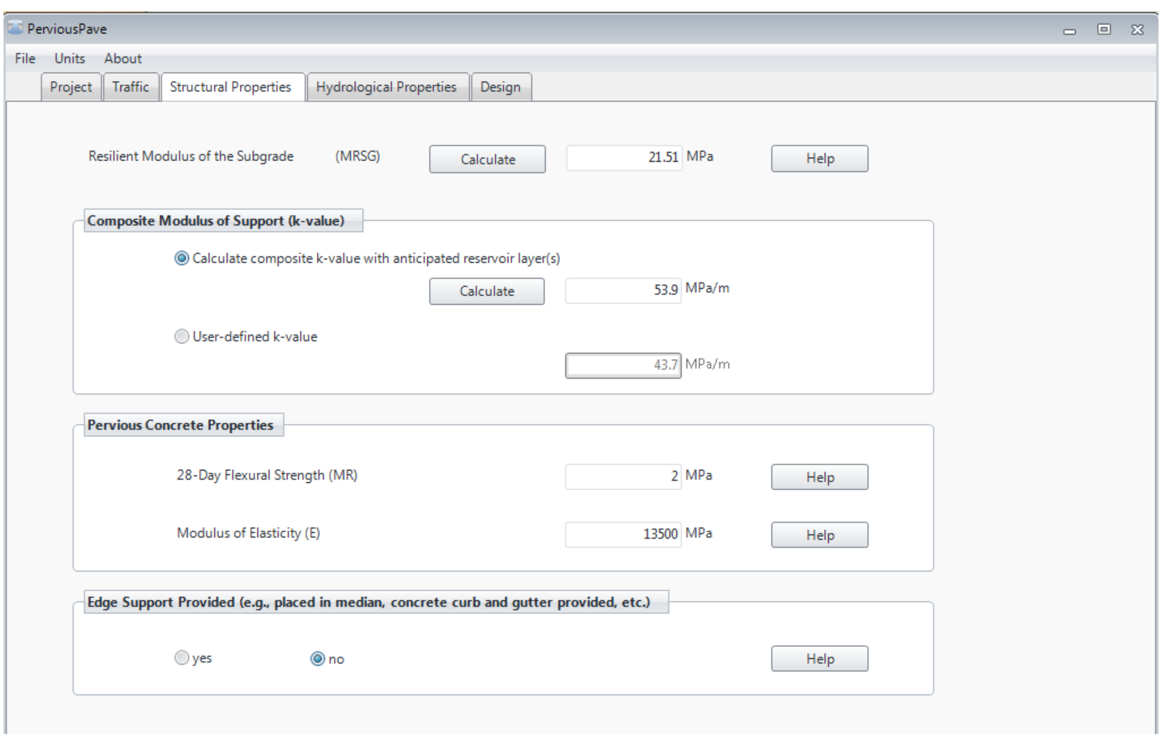

Figure 3. Structural Properties tab in PerviousPave.

Table 1. Layer Thicknesses for Sites 3 through 5 of the Referenced Research [20] and PerviousPave Design Results

	Reservoir Layer Thickness (mm)	Pervious Concrete Thickness (mm)
Site 3	200	250
Site 4	250	200
Site 5	200	200
PerviousPave Run #1	200	203
PerviousPave Run #2	250	190

As shown in Table 1, the PerviousPave structural analysis determines that 203 mm and 190 mm of pervious concrete are necessary on the 200 mm and 250 mm thick reservoir layers, respectively. Thus, structural designs with PerviousPave agree very well with the designs of sites 3 through 5 of the referenced research.

6.2 Hydrological Design Comparison – Inputs used in the hydrological design include:

- *Site Factors:* Although the referenced research reports site size, it does not report the non-pervious area to be drained through the pervious concrete area, which has a bearing on the volume of water that the pervious concrete system must process. Thus, it is assumed that the pervious concrete will process an area that is four times that of its own area. To simplify the comparison, consider just site 4 (Barrie, ON) of the referenced research, with an area of 250 m^2. Based on the assumptions made here, the non-pervious area to be drained is assumed as 1,000 m^2.
- *Permeability/Infiltration Rate of the Soil:* Because the permeability/infiltration rate of the soil is not reported in the research, it is assumed at 7 mm/hr, a typical value for clay loam soils.
- *Hydrological Details of the Concrete and Reservoir:* Although the referenced research found a void content of 29.1% for the pervious concrete [18], it is assumed that a more typical value of 15% is realized. The percent voids of the reservoir layer is assumed as 40%, a typical target percent voids for a reservoir layer and the default value in PerviousPave.
- *Hydrological Design Criteria:* Because no design storm precipitation is provided in the referenced research, the typical value for Buffalo, NY, USA of 57.15 mm is assumed. The maximum detention time of water in the pervious section is left at the default of 24 hours.

Based on these assumptions and those made in the Structural Design Comparison section above, PerviousPave again calculates the required pervious concrete thickness as 203 mm and the required reservoir layer thickness is calculated as 238 mm (Figure 4). These values are very close to those calculated by the researchers during their design of site 4 (see Table 1) using StreetPave for the structural design and the NRMCA's software for the hydrological design.

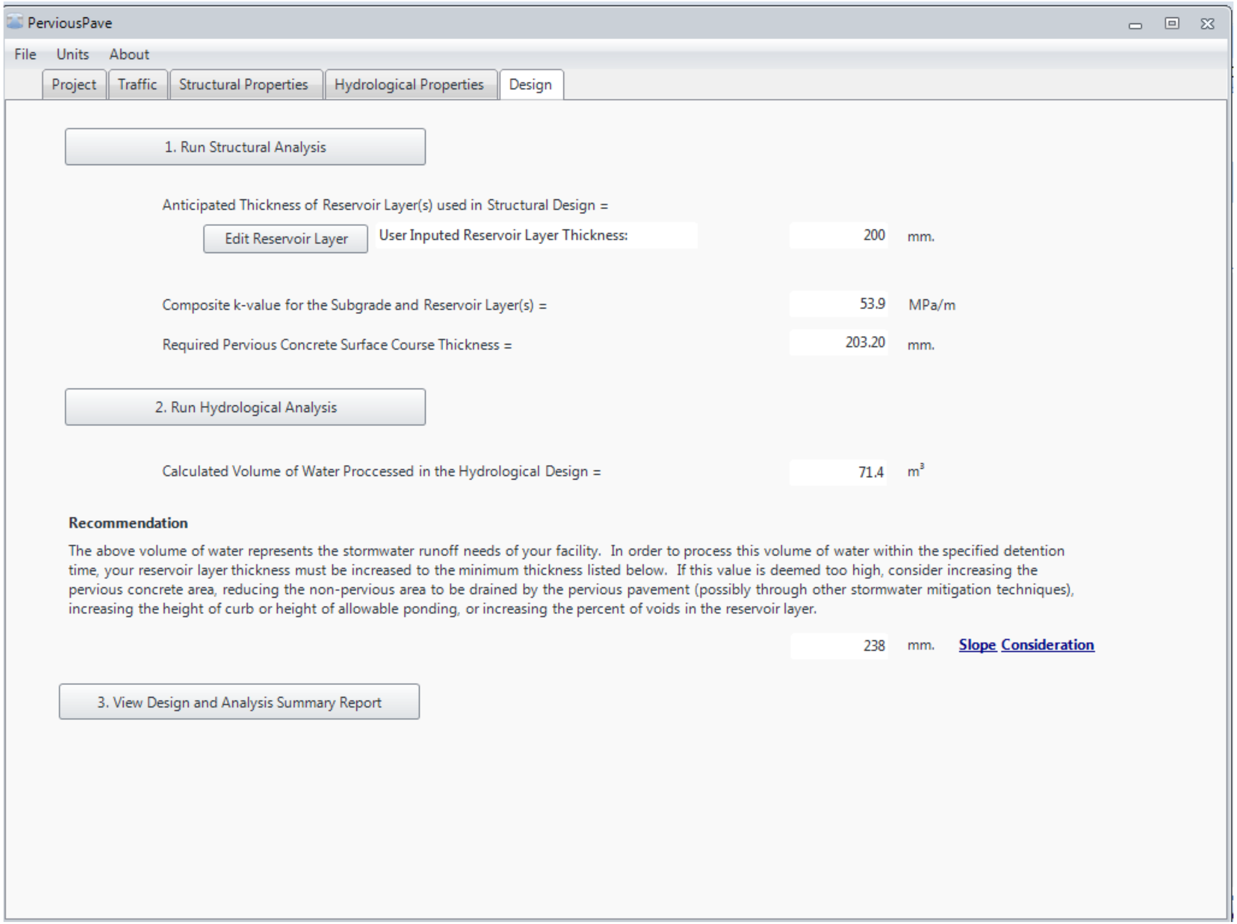

Figure 4. The Design tab in PerviousPave, showing the results of a comparative analysis with site 4 detailed in references 20 and 21.

7.0 Conclusions

PerviousPave has been developed through slight modification to and a combining of existing concrete pavement thickness and pervious pavement hydrological design methods. The software provides results optimized for both the structural and stormwater management requirements and is capable of 1) determining the required minimum pervious concrete pavement thickness based on the design traffic, design life, and other structural inputs, and 2) determining the required reservoir thickness necessary to satisfy stormwater management requirements based on volume of water to be processed by the pavement within the required maximum detention time. A comparison to pervious concrete sections developed as part of an ongoing research investigation in Canada validates that the pervious concrete and reservoir thickness are comparable to values calculated using other existing means.

8.0 References

1. *Stormwater Management with Pervious Concrete Pavements*, IS334P, American Concrete Pavement Association, Skokie, IL, 2009.
2. Henderson, V., and Tighe, S.L., *Design, Performance and Maintenance of Pervious Concrete Pavement in Canada*, Draft Progress Report, August 2010.
3. *Thickness Design of Concrete Pavements*, IS010.01P, Portland Cement Association, Skokie, IL, 1966.
4. Tayabji, S.D., and R.G. Packard. *Mechanistic Design of Concrete Pavements to Control Joint Faulting and Subbase Erosion*, Presented at the International Seminar on Drainage and Erodibility at the Concrete Slab-Subbase-Shoulder Interfaces, Paris, France, 1983.
5. *Thickness Design for Concrete Highway and Street Pavements*, EB109, Portland Cement Association, Skokie, IL, 1984.
6. Gotlif, A., J. Mallela, M.I. Darter. *Enhanced StreetPave PCC Thickness Design Procedures: Development of Models for Tridem Axles*, ERES Consultants, A Division of Applied Research Associates, Inc., Champaign, IL, 2004.
7. Titus-Glover, L., J. Mallela, M.I. Darter. *Enhanced PCC Fatigue Model for StreetPave*, ERES Consultants, A Division of Applied Research Associates, Inc., Champaign, IL, 2004.
8. *StreetPave*, MC003.01P, American Concrete Pavement Association, Skokie, IL, 2005.
9. *PerviousPave*, SW04, American Concrete Pavement Association, Skokie, IL, 2010.
10. Pindado, M.A., Aguado, A., and Josa, A. *Fatigue Behavior of Polymer-Modified Porous Concretes*, Cement and Concrete Research, Vol. 29, Issue 7, pages 1077-1083, 1999.
11. Watanabe, T., Todoroki, Y., and Iwa, S. *The Fatigue Characteristics and Structural Design of Porous Concrete Pavement with Flexibility*, Concrete Journal, Vol. 42, No. 4, pages 18-25, 2004.
12. Tamai, M., Mitzuguchi, H., Hatanaka, S., Katahira, H., Makazawa, T., Yanagibashi, K., and Kunieda, M. *Design, Construction and Recent Applications of Porous Concrete in Japan*, Proceedings of the JCI Symposium on Design, Construction, and Recent Applications of Porous Concrete, Japan Concrete Institute, 2004.
13. *Urban Hydrology for Small Watersheds*, Technical Release No. 55, Soil Conservation Service, U.S. Department of Agriculture, Washington, DC, 1986.
14. *Development Planning for Storm Water Management*, Los Angeles County Department of Public Works, CA, 2002.
15. For example of Rational Method, see: Viessmann, W., and Lewis, G.L. *Introduction to Hydrology*, 5^{th} Edition, Prentice Hall, 2003.
16. *Report of Committee on Maintenance of Joints in Concrete Pavements as Related to the Pumping Action of Slabs*, Proceedings of the Twenty-Eighth Annual Meeting, Highway Research Board, 1948, page 281.

17. *Subgrades and Subbases for Concrete Pavements*, EB204P, American Concrete Pavement Association, Skokie, IL, 2007.
18. Miner, M.A. *Cumulative Damage in Fatigue*, Trans. ASME, Vol. 67, 1945.
19. *MATS-User's Manual*, Computer Software MC012, Portland Cement Association, Skokie, IL, 1990.
20. Henderson, V., and Tighe, S.L. *Pervious Concrete Pavement Performance in Field Applications and Laboratory Testing*, Permeable Pavement Design and Technology Session of the 2010 Transportation Association of Canada Meeting.
21. Henderson, V., and Tighe, S.L. *Pervious Concrete Pavement Performance in the Canadian Freeze-Thaw Climate*, 11^{th} International Symposium on Concrete Roads, Seville, Spain, October 2010.
22. Strength Converter, ACPA Application Library, http://apps.acpa.org/apps/StrengthConverter.aspx, accessed 5/6/2011.