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Executive Overview – Building on StreetPave, a thickness design methodology for jointed plain concrete pavements, the American Concrete Pavement Association (ACPA) has adapted its design methodology for use in the structural design of pervious concrete pavements. Structural and hydrological design methods have been combined into software called PerviousPave, a user-friendly tool that provides results optimized for both the structural and stormwater management requirements. PerviousPave's hydrological design method is based primarily on modifications to the Los Angeles County method. The software 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 subbase/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.

This document details the background, purpose and assumptions made during the development of PerviousPave, and the equations used for both the structural and hydrological designs are included as appendices.

Background/Need for Design Method

Predecessors to PerviousPave – The Portland Cement Association (PCA) thickness design methodology for jointed plain concrete pavements, originally published in 1966 (*1*), used slab stress/fatigue as the sole design criterion for determining the required concrete thickness to carry the design traffic for applications such as highways and streets. In 1984, this design methodology was updated to include several new features, including consideration of pavement failure by erosion (pumping) and structural impact of edge support by way of concrete shoulders or curb and gutter sections (*2*, *3*). Another update to the design methodology came in 2005, when the American Concrete Pavement Association (ACPA) used the basic design methodology in the development of StreetPave, software tailored for thickness design of streets and roads (*4*). StreetPave incorporated an enhanced concrete fatigue model that includes a reliability component (*5*) and the ability to analyze tridem axles in the traffic spectrum (*6*), as well as recommendations for dowelling joints, among other updates.

Impetus for a Pervious Concrete Pavement Structural Design Software – While several viable options have existed during the past decade for the hydrological design of pervious concrete pavements, no design methodology or software for the structural design of pervious concrete pavements existed. In an attempt to have some logical basis for structural design, some pavement engineers reverted back to simple design theories such as Westergaard's solutions, while others attempted to apply more modern design methodologies. By 2008, the suggestion to use StreetPave for the structural design of pervious concrete pavements was published in at least two widely-circulated resources/journals (*7,8*).

Several design considerations inherent in StreetPave do not lend themselves to application for pervious pavement design. For example, StreetPave requires the use of dowel bars for design thicknesses greater than 8 inches, but pervious pavements never include dowel bars. StreetPave applies an evaluation of erosion/faulting as a design criterion, but hydraulic pressures on entrapped water under pervious slabs are likely quite different than under normal slabs. StreetPave also includes design options not appropriate for pervious applications (experience to date) including certain subbase material options (e.g. treated subbases) and traffic categories for heavy axle load distributions.

Because these inconsistencies could lead to erroneous results, ACPA does not recommend the use of StreetPave for the structural design of pervious concrete pavements. It is this reason, and the opportunity to fill a gap in technology, that led ACPA to develop dedicated structural design software applicable for pervious pavements.

From StreetPave to PerviousPave – StreetPave was adapted into PerviousPave in 2010. Aside from a few design variables that differ between pervious and conventional concrete pavements, such as the maximum strength, the use of dowel bars, the traffic distributions, and the types of subgrades/subbases/reservoir layers that are available, the primary updates in the adaptation of the existing thickness design methodology were the exclusion of erosion as a failure criterion and the inclusion of a hydrological design component. The fatigue equations used in the most recent version of StreetPave were also used in PerviousPave for reasons discussed later in this document.

PerviousPave Design Criteria and Assumptions

Structural/Fatigue Design and Compressive/Flexural Strength Testing – Although several studies have investigated the fatigue behavior of pervious concrete (*11, 12*), the limited mixture designs and number of samples used in these studies as well as other concerns, such as fatigue of 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 (*13*). 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 (*5*); see Appendix A for the equations used for structural design in PerviousPave.

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 and StreetPave assume such inputs to be comparable in nature (but not magnitude) to those used for conventional concrete pavements.

ACPA recognizes that these are assumptions based on current knowledge, which may change if new standards are released or future research disproves the assumptions. If improved strength testing and fatigue information comes to the forefront, ACPA will apply the new knowledge to enhance future versions of PerviousPave.

Hydrological Design – Many pervious concrete pavement hydrological design methodologies exist, including the Soil Conservation Service (SCS) Method (*14*), the Rational Method (*15*), the Los Angeles County Method (*16*), and many locally-tailored methods. Because of the lack of a unified voice on a preferred method, ACPA evaluated each one to determine which was most appropriate for incorporation into PerviousPave. An adaptation of the Los Angeles County Method (*16*) hydraulic design was chosen as the best fit. This design method 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 subbase/reservoir layer is adjusted (increased), as necessary, until the pervious concrete pavement structure is capable of meeting the required stormwater management requirements. Together, this method ensures that the optimal structural design and stormwater requirements are met for the project. The equations used for the hydrological design in PerviousPave are included in Appendix B.

No Erosion Failure Criterion – The erosion criterion in the StreetPave design methodology got its roots in early pavement performance research on pumping of soils and subbase layers. Cooperative studies by state highway departments and the PCA during the 1930's and 1940's identified three factors necessary for pumping to occur (*9*):

- A fine-grained subgrade or erodible subbase material,

- The presence of water between the pavement and the subgrade/subbase, and
- Fast moving, heavy loads to deflect the slabs (e.g., trucks, not automobiles).

Further field experience determined that undoweled joints or joints with poor load transfer represent a fourth contributing factor to pumping (*10*). These four factors are the basis for the erosion model in the current StreetPave design methodology.

Pervious concrete pavements typically are used in applications that do not have fast moving, heavy loads, and the subbase/reservoir layer typically consists of a non-erodible material. Also, the voids in pervious concrete mixtures are likely to help dissipate hydraulic pressures under vehicle loads. Although this has not been researched directly, it is hypothesized that water near the slab/subbase interface has numerous escape locations (the voids in the pervious concrete) compared to a standard concrete mixture in which the only escape path for water and fine subbase/subgrade material is through transverse and longitudinal joints to the pavement surface. With pervious concrete, hydraulic pressures and pumping action is minimized or eliminated.

Because of these considerations and a lack of evidence of erosion as a failure mode for pervious concrete pavements in the field, ACPA believes that subbase/subgrade erosion is not a valid failure mode for pervious concrete pavements. Therefore, in PerviousPave fatigue is the sole failure criterion for a pervious concrete pavement from a structural standpoint.

No Surface Distress Failure Criterion – Although surface problems such as surface raveling from turning motions of heavy vehicles and freeze-thaw damage are possible distress modes for pervious concrete pavements, acceptable models have not been developed to predict failure from such distresses. Regardless, resistance of the surface to such variables is controlled strictly by materials and construction techniques. Since PerviousPave is a structural and hydrological design software tool, it is predicated on best practices for materials and construction. This is an assumption that is parallel to and consistent with the omission of material-related distresses in other concrete and asphalt pavement structural design methodologies, such as found in StreetPave, AASHTO 93, and M-E PDG.

ACPA will apply new distress models to enhance PerviousPave if and when they become available.

Appendix A: Structural Design Equations

Fatigue is the sole failure criterion for the structural design of pervious concrete pavement in PerviousPave. Considering the cumulative damage caused by single, tandem, and tridem axle loads, the total fatigue damage (FD_{total}) can be written as:

$$FD_{total} = FD_{single} + FD_{tandem} + FD_{tridem} \tag{1}$$

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 and load group in Equation 1 is computed per Miner's damage hypothesis (*17*):

$$FD = \frac{n}{N_f} \tag{2}$$

where,

n = number of load applications (calculated from the user inputted traffic data)
N_f = allowable applications to failure

The total allowable applications to failure can be estimated as (*5*):

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

where,

SR = stress ratio, %
P = probability of failure, %

In PerviousPave, the probability of failure is calculated as:

$$P = 1 - R * \frac{SC}{50} \tag{4}$$

where,

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

The stress ratio is simply the stress divided by the strength of the material:

$$SR = \frac{\sigma_{eq}}{MR} \tag{5}$$

where,

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

The equivalent stress, assumed at the slab edge, is computed using the following (*3*, *6*):

$$\sigma_{eq} = \frac{6 * M_e}{{h_c}^2} * f_1 * f_2 * f_3 * f_4 \tag{6}$$

where,

M_e = equivalent moment, psi

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

h_c = concrete pavement thickness, in.
f_1 = adjustment factor for the effect of axle loads and contact area

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

f_2 = adjustment factor for a slab with no concrete shoulder (*18*)

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

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)
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

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

where,

l = radius of relative stiffness, in.

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

E = modulus of elasiticty of the concrete, psi
k = modulus of subgrade 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 pavement thickness and calculates FD_{total} for each axle type and load group until the point that FD_{total} reaches 100 percent, the limiting structural design criterion.

Appendix B: Hydrological Design Equations

The structural design algorithm produces a minimum necessary pervious concrete thickness to service the design traffic over the design life of the pavement. To maintain this condition, the pervious concrete pavement thickness is held constant during the hydrological design. The adjustments PerviousPave will consider, to ensure stormwater requirements are met, include increasing the subbase/reservoir layer thickness, if necessary, or adding a subbase/reservoir layer if one was not already included in the structural design. If the hydrological design results in a thicker subbase/reservoir layer section than was included in the structural design, the structural design will be more conservative; if this is the case, the PerviousPave user is notified that they might choose to re-run the structural design to determine if a thinner pervious concrete pavement section is possible.

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 (*16*) formula for the required pervious concrete area is:

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

where,

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

Equation 13, as used in the Los Angeles County Method, assumes that the entire volume of water will be contained within and processed by the subbase/reservoir layer. If, instead, the capacity of the pervious concrete layer, the capacity of the subbase/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:

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

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 (i.e., pervious concrete thickness), the thickness of the subbase/reservoir layer can be determined as:

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

The detention time is then 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 (*16*), again assuming that the subbase/reservoir layer will process the entire volume of water, suggests using this expression to solve for the subbase/reservoir layer thickness:

$$h_s = \frac{E*t_d}{r_s} \tag{16}$$

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

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

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

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

If the calculated detention time is less than the maximum detention time inputted by the user, t_d^*, the design subbase/reservoir layer thickness calculated by Equation 15 is sufficient for the volume of water to be processed by the paved area.

If the calculated detention time is greater than t_d^*, however, the pervious concrete pavement area is not large enough for the soil to process the design volume of water within the required detention time. In such cases, the pervious concrete area can be increased or, if this cannot be done due to site restrictions, the non-pervious area can be decreased or the required detention time revisited. Ultimately, if the reservoir layer(s) are conservatively designed such that they will hold the volume from the design storm, the detention time is irrelevant (as is the infiltration rate of the soil) as long as there is sufficient time between design storms for the water to be processed into the soil. If the paved area is to be increased, the required pervious area based on the maximum detention time becomes:

$$A_p = \frac{12*V}{t_d^**E} \tag{19}$$

This appendix contains the basic equations that are used in PerviousPave; adjustments to these equations or the assumptions they are based on are then made, as necessary, to account for each individual design (e.g., setting h_{curb} and h_c both equal to zero if the curb and pervious concrete surface course are excluded from the design, as is often done in a wet-freeze environment).

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Contact for Questions

If you have any questions or comments about PerviousPave, please contact Robert Rodden, ACPA's Director of Technical Services and Product Development, at 847.972.9808 or rrodden@acpa.org.