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Structural Design Guidelines for Pervious Concrete Pavements

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By

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ABSTRACT

Pervious pavements have gained popularity in recent years as the transportation industry focuses on sustainability and environmental impact. This research investigated the structural design of pervious concrete pavements. There is no standard design method; therefore, the goal was to lessen ambiguity surrounding the use of pervious concrete for pavement structures. By characterization of the rigid pavement design equation from the *1993 AASHTO Structural Design Guide for Design of Pavement Structures* through laboratory exploration and review of existing literature, a guide was created to assist engineers in the design of pervious concrete pavements.

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INTRODUCTION

One of the biggest concerns of the transportation industry today is environmental impact. Porous pavements have become an increasingly implemented method due to their sustainable benefits, such as recharging groundwater supplies and decreasing urban heat-island effects, as depicted on *perviouspavement.org*. Pervious concrete in particular requires less cementitious material to produce, which could decrease the carbon footprint and embodied energy of a project, according to *bayareaperviousconcrete.com*.

However, there seem to be missed opportunities to use pervious concrete for pavements in the United States. Since it is a relatively new material, there is no standard pervious concrete pavement structural design method. Additionally, there are no existing standards on how to test the structural properties of pervious concrete in a laboratory setting. The goal of this research was to lessen the ambiguity about using pervious concrete in a pavement structure. Therefore, by characterizing inputs of the rigid pavement design equation from the American Association of State Highway and Transportation Officials' (AASHTO) *1993 AASHTO Guide for Design of Pavement Structures*, hereafter referred to as the 1993 AASHTO Guide, a guide was created to assist engineers in the design of pervious concrete pavement structures.

BACKGROUND

Design procedures for pervious concrete pavements are normally focused on hydrologic components, like the thickness of the open-graded stone reservoir layer that is meant to store infiltrated storm water and slowly discharge it into the subgrade soil. However, with pervious concrete piquing interest for use on local low-volume roads, a shift in focus to structural capacity is needed. Components of a pervious concrete pavement structure include the surface layer of pervious concrete, the stone reservoir layer(s), and the underlying subgrade soil, as shown in Figure 1.

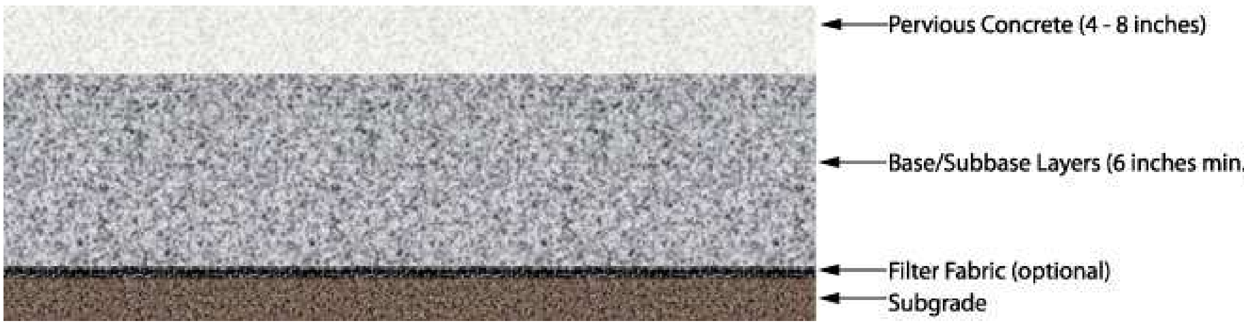

Figure 1. Pervious Concrete Pavement Structure Components (from FHWA TechBrief: Pervious Concrete, December 2012)

STRUCTURAL DESIGN PROCEDURE

One of the most commonly used methods for the design of pavement structures in the United States is from the 1993 AASHTO Guide. Empirical equations for flexible and rigid pavements were derived from tests performed as part of the American Association of State Highway Officials (AASHO) Road Test in the late 1950's in Ottawa, Illinois. Nomographs were also produced using the equation inputs to provide a user-friendly design method. The AASHTO design procedure for rigid pavements is described in a later section of this document.

Limitations

Because the AASHO Road Test was performed in a single location in Illinois, there are some limitations to keep in mind. The climate of Ottawa, Illinois is representative of a typical northern U.S. climate, with lows around 20 degrees Fahrenheit and highs around 70 degrees Fahrenheit. This means the pavement materials did not encounter extreme cold or heat during the tests. However, pavements did experience freezing temperatures and a potential for freeze and thaw. That being said, the gradation for the base course included 10 percent mass passing the number

200 sieve, meaning it could have been especially susceptible to freeze and thaw, according to *pavementinteractive.org*. This should be kept in mind as the configuration of pervious concrete provides resistance to freeze and thaw.

The only pavement surface materials tested during the AASHO Road Test were conventional asphalt and concrete; no permeable pavements were constructed. Additionally, the in-situ soil was the only subgrade tested, so applying the 1993 AASHTO design method to different subgrades may produce imprecise results. Furthermore, construction methods for pervious concrete pavements involve very little compaction of the subgrade before the addition of the stone reservoir layer, whereas the subgrade in the AASHO Road Test was heavily compacted.

All of these limitations present the question of how appropriate the 1993 AASHTO design method is for the design of pervious concrete pavements as well as conventional pavements with varied subgrade soils. This research does not address these limitations in particular, therefore, there is still a need for investigation into these issues.

Laboratory Research

In order to correctly characterize the inputs for this structural design method, the strength and engineering properties of pervious concrete need to be determined. Therefore, tests for compressive strength, flexural strength, elastic modulus, and Poisson's ratio were performed using standards from the American Society for Testing and Materials (ASTM). Through an extensive review of the existing literature, typical values for compressive and flexural strength were found. Smith (2016) determined compressive strength of a coarse-graded pervious mix (similar to the mixtures tested in this research) to be about 1400 psi after 28 days. As for flexural strength, results tend to be variable as is the nature of pervious concrete, and can range from 150 psi to 550 psi, according to *perviouspavement.org* (2011).

Pervious concrete mixtures were designed using the National Ready Mixed Concrete Association's *Guideline to Proportioning Pervious Concrete Mixtures* (NRMCA, 2009). Mixtures with varying percentages of fly ash were made to test how the structural properties would differ between specimens when cement was substituted with a supplementary cementitious material. Substitutions of 15 percent and 30 percent fly ash were chosen in addition to a control mix with portland cement only. The sections which follow describe laboratory methods and design standards used for pervious concrete mixtures.

Gradation Selection

The NRMCA's guide suggested using the AASHTO No. 67 gradation for pervious concrete mix designs. However, most pervious concrete mixtures exclude fine aggregates, or those passing the No. 4 sieve. Therefore, the gradation was adjusted to only include the aggregate sizes from the gradation that would be retained on the No. 4 sieve and above. These sizes included aggregates retained on the No. 4, 3/8", and 1/2" sieves, as shown in Table 1.

Table 1. Aggregate Gradation for Pervious Concrete Mix

Sieve Size	Percent Passing
1/2"	67%
3/8"	33%
No. 4	0%

Water to Cementitious Material Ratio Selection

For pervious concrete batching, optimizing the paste consistency is crucial, as the paste must be thin enough to cover all aggregates, yet viscous enough to avoid experiencing drain-down. Therefore, ASTM C305-14 was used to make multiple paste batches with different water to cementitious material ratios (W/CM). ASTM C1437-15 was followed in order to test the consistencies using a flow cone mold and tamping table, as shown in Figure 2. NRMCA's guide suggested that the paste was at the correct consistency for batching when the spread reached a diameter of 5 inches after the tamping process. As expected, the zero percent, 15 percent, and 30 percent fly ash pastes reached a 5-inch spread at different W/CM ratios. Because of the spherical shape of fly ash particles, the 30 percent fly ash paste reached a 5-inch spread at a smaller W/CM ratio than the other two. The W/CM ratios selected are provided in Table 2.

Table 2. Water to Cementitious Material Ratios for each Mix Design

0% FA Mix	15% FA Mix	30% FA Mix
0.41	0.38	0.375

Figure 2. Flow Cone and Tamping Table Setup for Testing Paste Consistency

Compressive Strength (f'_c)

Three sets of pervious concrete cylinders measuring four inches in diameter and eight inches tall were batched in a single day, following the standard practice of ASTM C192/C192M-18. Once the cylinders were batched, they were stored overnight to set and then were submerged in a climate-controlled curing tank. Compressive strength tests were performed on days 7, 14, and 28, as it is both common practice and suggested by ASTM. The batching and testing configurations, as well as the change in compressive strength over time, are shown in Figures 3 and 4, respectively. The decrease in compressive strength over time is unusual and further research is needed to understand why this occurred.

Figure 3. Batching and Testing Pervious Concrete Cylinders

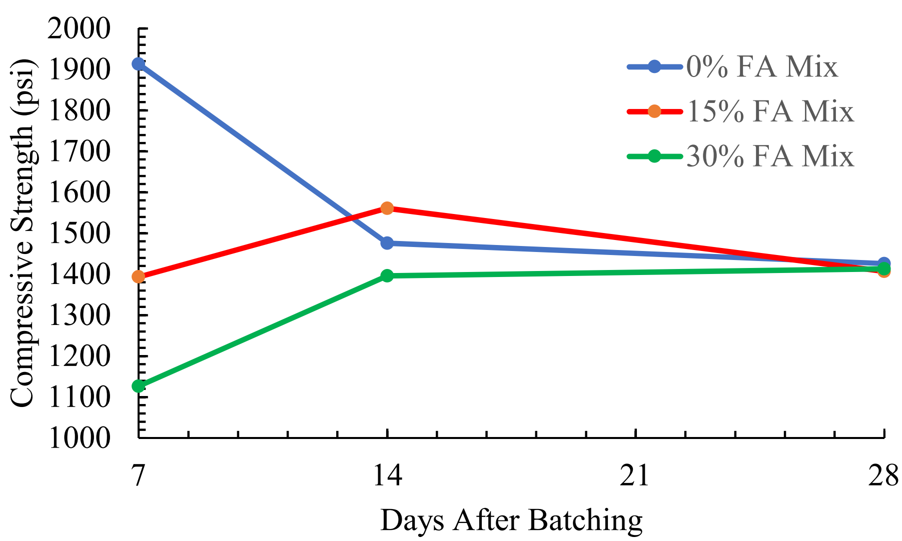

Figure 4. Compressive Strength Change Over Time of Pervious Concrete Cylinders

Flexural Strength

Due to time constraints, only one beam per mix design was batched in order to determine the pervious concrete's modulus of rupture, which is a measure of flexural strength. The 3-point beam test was run after 28 days of curing in a temperature-controlled bath and in accordance with ASTM C78/C78M-18. Equation 1 was used to calculate the modulus of rupture for all beams, since fractures were within the middle third of each beam. A summary of the flexural strength test results is given in Table 3, and the beam specimens are shown in Figure 5.

$$R = \frac{PL}{bd^2} \tag{1}$$

where:
R = *modulus of rupture (psi)*
P = *maximum applied load indicated by testing machine (lbf)*
L = *span length (in)*
b = *average width of specimen at the fracture (in)*
d = *average depth of specimen at the fracture (in)*

Table 3. Flexural Strength of Pervious Concrete Beams after 28 Days

0% FA Mix	15% FA Mix	30% FA Mix
229 psi	228 psi	249 psi

Figure 5. Pervious Concrete Beams for Flexural Strength Testing

Concrete Elastic Modulus & Poisson's Ratio

Laboratory determination of the elastic modulus and Poisson's ratio of a hardened concrete mixture requires measuring and recording the stress applied to a test specimen, which is related to the applied load, and the resulting strain experienced by the specimen. Strain is calculated using both axial and lateral deflections of the specimen under the applied load. Finding an accurate and feasible method of measuring the axial and lateral deflections of the pervious concrete cylinders was by far the most challenging laboratory task. These deflection values are of relatively small magnitude. Therefore, they are very difficult to measure with repeatable precision and accuracy. Moreover, the physical nature of the pervious concrete made it impossible to use conventional, contact-based strain gauge devices, as the voids on the surface prohibited the stabilization of the instrumentation cage.

Therefore, a different axial deflection measuring device was used. It had two LVDT's, or linear variable differential transformers, that were attached to metal rings that fit over the specimen. The rings had fewer places to attach to the specimen, so it was able to grip the specimen better than other devices.

In order to determine lateral deflections, an extensometer chain was secured around the middle of the cylinder. The extensometer actually measured the change in the specimen's circumference, from which the lateral deflection was determined. Equations 2 and 3 show how the recorded change in circumference is converted to a change in radius.

$$\theta_i = 2\pi - \frac{l_C}{(R_i + r)} \tag{2}$$

where:
θ_i = *angle subtended by initial chord length (radians)*
l_C = *chain length (inches)*
R_i = *initial radius of specimen (inches)*
r = *radius of roller*

$$\Delta R = \frac{\Delta l}{2[\sin\left(\frac{\theta_i}{2}\right) + \left(\pi + \frac{\theta_i}{2}\right)\cos\left(\frac{\theta_i}{2}\right)]} \tag{3}$$

where:
ΔR = *change in specimen radius (inches)*
Δl = *extensometer output (inches)*

Per ASTM C469/C469M-14, the sample needed to be loaded to 40 percent of its measured compressive strength. Keep in mind that these tests are not necessarily meant to be of a destructive nature, unlike compressive and flexural test methods. All cement-only specimens and 15 percent fly ash specimens were tested with varied results throughout. However, the first 30 percent fly ash specimen that was tested crushed before it reached the peak load and damaged the measuring devices. Unfortunately, even the data obtained from testing the cement-only and 15 percent fly ash specimens was too inconsistent to draw logical conclusions. This could be due to variable structural capacities of the specimens and/or ill-fitting equipment.

Laboratory Conclusions

In conclusion, different methods are needed to measure both compressive strength and minute deflections in the specimens. The chosen cylinder size seemed too small to represent the true potential of the aggregate matrix in a pavement, since there was no room for substantial coarse aggregate-bonding within the four-inch diameter, whereas a reasonably sized slab or a larger cylinder may perform substantially better under respective tests. Further research is needed to confirm this hypothesis. As for the determination of elastic modulus and Poisson's ratio, using a non-contact strain measurement method to determine deflections would be significantly more precise than current technology for these specimens. Overall, the void structure of pervious concrete just isn't conducive to most conventional testing procedures.

DESIGN INPUTS

Equation 4 is an empirical equation derived from the AASHO road test performed on rigid pavements. There are many individual inputs required to solve for the slab thickness of concrete, which is represented in the equation as D and solved for in inches.

$$\log_{10}(W_{18}) = Z_R S_0 + 7.35\,\log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{3}\right)}{1+\frac{1.624\times 10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32\,p_t)\log_{10}\left(\frac{S_c' C_d\left(D^{0.75}-1.132\right)}{215.63\,J\left(D^{0.75}-\frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right) \quad (4)$$

where:

W_{18} = *estimated amount of 18,000 lb equivalent single-axle loads (ESAL's)*
Z_R = *standard normal deviate; relates to the design's reliability*
S_o = *combined standard error of traffic & performance prediction; design's reliability*
ΔPSI = *difference of* p_o*, initial serviceability index &* p_t*, terminal serviceability index*
S'_C = *modulus of rupture of concrete, which relates to flexural strength (psi)*
C_d = *drainage coefficient*
J = *load transfer coefficient, which relates to the efficiency of load transfer*
E_C = *elastic modulus of concrete (psi)*
k = *modulus of subgrade reaction (pci)*

Design Traffic Loads (W_{18})

Since porous pavements are not often used for application on highways, this example scenario will be for urban streets instead. The three design traffic loads that were chosen are representative of a minimum, mean, and maximum of an assumed general load range on urban streets, shown in Table 4.

Table 4. Design Traffic Loads for Urban Street in ESAL's

Minimum	Mean	Maximum
500,000	1,000,000	1,500,000

Design Reliability (Z_R, S_o)

A value for the standard normal deviate of 75% was chosen based on an average of values from the 1993 AASHTO Guide, shown in Table 5, since pervious concrete tends to be more variable in nature than conventional concrete. As for the standard deviation, a value of 0.35 was taken from the Arkansas Department of Transportation (ARDOT) *Roadway Design Plan Development Guidelines* (ARDOT, 1998).

Table 5. Adaptation of the 1993 AASHTO Guide's Table 2.2 - Suggested Levels of Reliability for Various Functional Classifications

Functional Classification	Urban	Rural
Interstate/Freeways	85-99.9	80-99.9
Principal Arterials	80-99	75-95
Collectors	80-95	75-95
Local	50-80	50-80

Allowable Serviceability Change (ΔPSI)

The allowable serviceability change was taken to be 2.0 from the ARDOT *Roadway Design Plan Development Guidelines*. This value results from an initial serviceability index of 4.5 and a terminal serviceability index of 2.5.

Concrete Flexural Strength / Modulus of Rupture (S'C)

Since all three flexural strength tests on the beams had similar results, a value of 230 psi was chosen for the flexural strength in this scenario. Various researchers have published correlations between the flexural strength and compressive strength of concrete; Rao (2012) and his colleagues summarized these efforts. The most common relationship is shown in Equation 5. Rao's summary suggests that the "b" coefficient in Equation 5 is most commonly 0.5, producing a relationship between the flexural strength and the square-root of the compressive strength. The "a" coefficient was found to be 7.5. When calculating the "a" coefficient produced from the resulting compressive strength and flexural strength of 1400 psi and 230 psi, respectively, in this study the coefficient is found to be a value of 6.15.

$$S'_C = a(f'_C)^b \tag{5}$$

<u>where</u>:
S'_C = flexural strength (psi)

f'_C = compressive strength (psi)
a, b = laboratory-based coefficients

Drainage Coefficient (C_d)

In most cases, the drainage coefficient is chosen to be a value of 1.0, since it is assumed that water won't sit within the pavement layer but will instead drain off and into a stormwater collection system. The same value of 1.0 will be used for the drainage coefficient in this scenario, because the water is expected to drain through the pervious concrete pavement and into the reservoir layer, meaning no water will be suspended within the surface layer.

Load Transfer Coefficient (J)

For this example scenario, there are no load transfer devices, or dowel bars, between slabs. In general, pervious concrete pavements are built without load transfer in mind, as the open void structure allows for more movement and less cracking. Therefore, a value of 4.0 was used, which is within a range taken from the 1993 AASHTO Guide's suggestion for plain jointed pavement with asphalt shoulders. These values are shown in Table 6.

Concrete Elastic Modulus (E_C)

The measurements taken in the lab did not provide estimates that were reliable enough to be used in this design scenario, therefore the most commonly used relationship between compressive strength and elastic modulus for conventional concrete, given in Equation 6, will suffice for determining a value for the elastic modulus. A value for compressive strength of 1400 psi results in a value of 2,132,745 psi for elastic modulus.

$$E_C = 57{,}000\sqrt{f'_C} \qquad (6)$$

<u>where</u>:
E_c = elastic modulus (psi)
f'_C = compressive strength (psi)

Table 6. Adaptation of the 1993 AASHTO Guide's Table 2.6 – Recommended Load Transfer Coefficient for Various Pavement Types and Design Conditions

Shoulder Material	Asphalt		Tied PCC	
Load Transfer Devices	Yes	No	Yes	No
Plain Jointed & Jointed Reinforced	3.2	3.8-4.4	2.5-3.1	3.6-4.2
Continuously Reinforced	2.9-3.2	-	2.3-2.9	-

Modulus of Subgrade Reaction (k)

The value for modulus of subgrade reaction was found by using the 1993 AASHTO Guide's "Chart for Estimating Composite Modulus of Subgrade Reaction…", displayed in Figure 6. This chart requires knowledge of the subbase thickness, subbase elastic modulus, and roadbed soil resilient modulus in order to estimate a value for k. A value for subbase thickness of 18 inches was chosen, since the open-graded stone reservoir layer will be at least 18 inches thick in order to hold and slowly diffuse water into the subgrade. As for the subbase elastic modulus, a value of 15,000 psi was chosen from the lower bound range for 'Unbound Granular Materials' given in Table 7. Lastly, the roadbed resilient modulus was chosen to be 7000 psi; the median value available on the chart, since there are no actual soil samples to test. These inputs result in a 'k' value of about 490 pci.

Table 7. Adaptation of the 1993 AASHTO Guide's Table 2.7 – Typical Ranges of Loss of Support actors for Various Types of Materials

Type of Material	**Elastic Modulus (psi)**	**Loss of Support**
Cement Treated Granular Base	1M – 2M	0-1
Cement Aggregate Mixtures	500,000 – 1M	0-1
Asphalt Treated Base	350,000 – 1M	0-1
Bituminous Stabilized Mixtures	40,000 – 300,000	0-1
Lime Stabilized	20,000 – 70,000	1-3
Unbound Granular Materials	15,000 – 45,000	1-3
Fine Grained/Natural Subgrade Materials	3,000 – 40,000	2-3

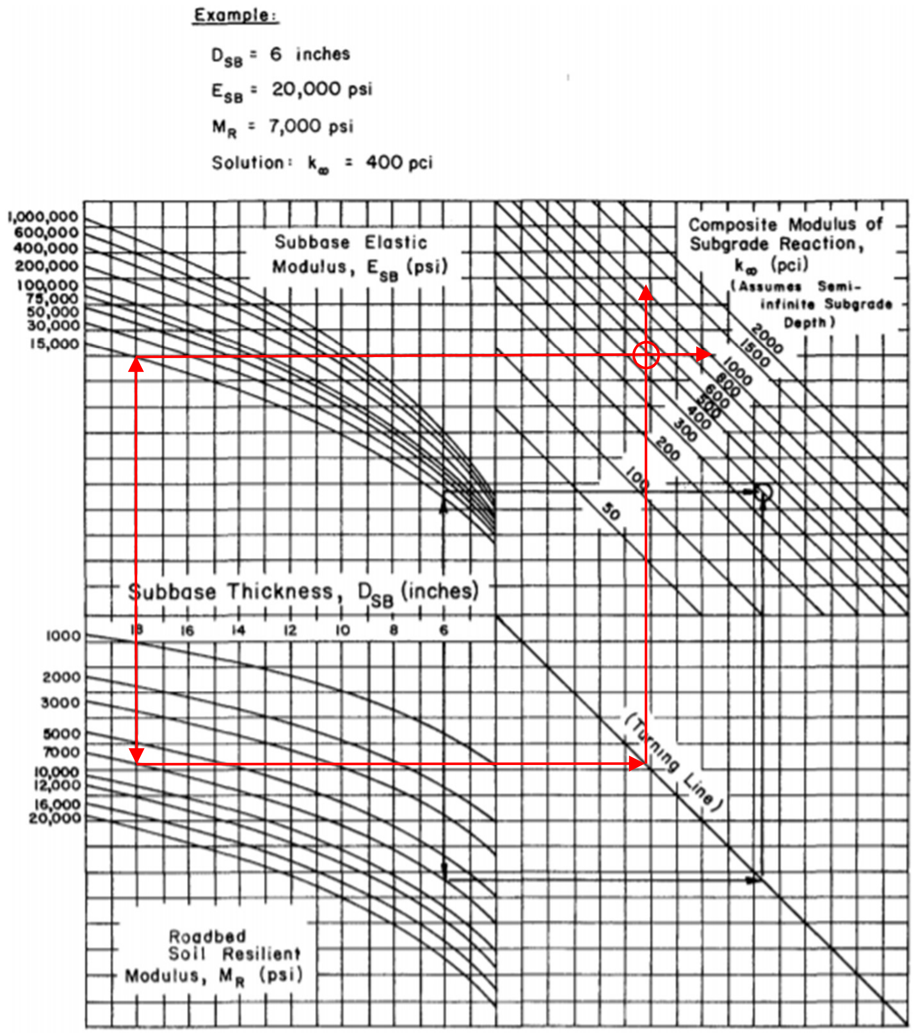

Figure 6. Chart for Estimating Composite Modulus of Subgrade Reaction (AASHTO, 1993)

Table 8 summarizes the inputs required for the structural design of a pervious concrete pavement using the 1993 AASHTO method.

Table 8. Summary of Structural Design Inputs for Pervious Concrete

Design Input	Value(s)	Source
Design Traffic Load (W_{18})	500K, 1M, 1.5M	Assumed
Standard Normal Deviate (Z_R)	75%	AASHTO Guide (1993)
Standard Deviation (S_o)	0.35	ARDOT Guide
Allowable Serviceability Change (ΔPSI)	2	ARDOT Guide
PCC Flexural Strength (S'_C)	230 psi	Laboratory Testing

Drainage Coefficient (C_d)	1.0	ARDOT Guide
Load Transfer Coefficient (J)	4.0	AASHTO Guide (1993)
PCC Elastic Modulus (E_C)	2,132,745 psi	Laboratory Testing
Modulus of Subgrade Reaction (k)	490 pci	AASHTO Guide (1993)

DETERMINING PAVEMENT LAYER DEPTHS

The final step in this structural design guide for pervious concrete pavement is to determine what thicknesses of pavement and base materials are needed to accommodate the various inputs. The following subsections go into detail on how to determine the thicknesses of each pavement layer.

Pervious Concrete Surface Layer

Once all the necessary inputs are determined, Equation 4 is solved to provide the required pavement slab thickness. The resulting pervious concrete pavement thicknesses for each of the three design traffic loads are displayed in Table 9.

Table 9. Resulting Pervious Concrete Pavement Thickness (D) for Various Traffic Loads

Design Traffic Load (ESAL's)	Pavement Thickness (Equation 4) (in)	Design Pavement Thickness (in)
500,000	10.23	10.5
1,000,000	11.52	11.5
1,500,000	12.32	12.5

Stone Reservoir Layer

This layer is meant to hold infiltrated stormwater until it is dispersed into the subgrade below. The thickness of this layer depends on a multitude of factors that can be determined with a hydrologic analysis. These factors include permeability of the pervious concrete, stone reservoir layer, and subgrade soil(s), the general depth of the groundwater table, the capillary rise of the soil(s), and others. The hydrologic design of pervious concrete pavements is beyond the scope of this research; however, more information can be found on *perviouspavement.org* under the 'Design' dropdown tab.

OTHER DESIGN CONSIDERATIONS

It should be noted that a sensitivity analysis of the AASHTO structural design equation (Equation 4) suggests that the equation is significantly less sensitive to many of the design inputs which are only 'estimated' in this study. For example, the PCC elastic modulus and the composite modulus of subgrade reaction (k) affect the estimated slab thickness to a much smaller degree than the flexural strength of concrete – for which actual laboratory measurements are available. Other inputs, such as reliability, standard deviation, serviceability index, etc., are taken from published specifications of a highway agency. Overall, the inputs used in this study related to the structural design of the pervious concrete slab represent a reasonable approach for design.

CONCLUSIONS & RECOMMENDATIONS

Overall, the 1993 AASHTO Guide design procedure, using the strength properties determined for this particular pervious concrete mix, provides reasonable pavement thicknesses. Although a concrete pavement surface thickness of ten to twelve inches is not conventional for low volume applications, according to the American Concrete Pavement Association (ACPA) *Design of Concrete Pavement for City Streets*, it is constructible in the field.

However, it is recommended that the 1993 AASHTO Guide not be the only design method explored when pervious concrete is involved. Designers must recognize the limitations and empirical nature of the 1993 AASHTO Guide, as well as the current lack of reliable data related to the engineering properties of pervious concrete. Certainly more research is needed to fully realize the potential of pervious concrete pavements for traffic applications.

Currently, designers must perform laboratory tests on actual pervious mixtures in order to determine their structural properties for proper design. Regardless of the design method, new methods for determination of modulus of elasticity and Poisson’s ratio are needed so that designs are based directly on the properties of a specific mix design. This study highlights this need, and provides a call-to-action for furthering knowledge, technology, and testing procedures with respect to pervious concrete.

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