Development of a Specification for Porous Asphalt Pavements

FINAL REPORT

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Report Number: CT-2300-F-18-3

April 16, 2018

SPR-2300

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Disclaimer

Acknowledgments

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Standard Conversions

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
CT-2300-F-18-3</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2">4. Title and Subtitle
Development of a Specification for Porous Asphalt Pavements
Final Report</td><td>5. Report Date
April 16, 2018
6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Scott Zinke, James Mahoney</td><td>8. Performing Organization Report No.
CAPLAB 05-2018</td></tr>
<tr><td colspan="2">9. Performing Organization Name and Address
University of Connecticut
Connecticut Transportation Institute
270 Middle Turnpike, U-5202
Storrs, Connecticut 06269-5202</td><td>10 Work Unit No. (TRIS)
N/A
11. Contract or Grant No.
CT Study Number SPR-2300</td></tr>
<tr><td colspan="2">12. Sponsoring Agency Name and Address

Connecticut Department of Transportation
2800 Berlin Turnpike
Newington, CT 06131-7546</td><td>13. Type of Report and Period Covered
Final Report
7-1-2016 through 4-1-2017
14. Sponsoring Agency Code
SPR-2300</td></tr>
<tr><td colspan="3">15. Supplementary Notes
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration</td></tr>
<tr><td colspan="3">16. Abstract
Porous Pavement Structures (PPS) have many benefits, including reduced or eliminated runoff, filtering of runoff and regeneration of groundwater. These structures have been used successfully across the United States for several years. In addition to adequately draining stormwater, there are a number of criteria these structures need to meet. These include adequate structural continuity to resist deformation from traffic loading, adequate asphalt binder performance to resist breakdown from oxidation and adequate void capacity in the subsurface reservoir layer to hold drained runoff while infiltration into the ground occurs. CTDOT currently has no specification for the construction of PPS or the production of PPS stone and/or asphalt material layers. This research located and reviewed specifications in existence elsewhere, interviewed asphalt pavement producers, and developed a suitable PPS specification for CTDOT. Development of criteria for design, performance, site selection and use of appropriate materials for PPS is included in the study analysis.</td></tr>
<tr><td>17. Key Words

asphalt pavement, porous pavement, permeable pavement, drainable pavement, pervious structure, open-graded pavement, water infiltration, stormwater percolation, stormwater runoff quality, porous pavement specification</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. The report is available on-line from National Transportation Library at http://ntl.bts.gov.</td></tr>
<tr><td>19. Security Classif. (of report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
55
21. Price</td></tr>
<tr><td>Form DOT F 1700.7 (8-72)</td><td colspan="2">Reproduction of completed page authorized</td></tr>
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Report Structure and Content

This report is structured to provide a summary of the work performed by the research team as part of the research project. The largest part of this project was the literature review and interviews with the Connecticut hot mix asphalt producers that supply porous asphalt materials. The report also contains conclusions and recommendations gleaned from the extensive literature review.

A draft special provision along with a draft special provision guidance document based on the best practices for Connecticut are contained in Appendix A and B respectively.

Introduction and Background Summary

Porous asphalt pavements (sometimes denoted as permeable pavements or pervious pavements) have been used successfully for many years throughout the United States as a means to reduce or eliminate stormwater runoff as well as to improve the quality of stormwater runoff. This is achieved by allowing the stormwater to penetrate completely through the asphalt pavement surface course(s) into a stone reservoir after which the water can then percolate into the soil over time. The construction of porous pavements is typically more expensive than traditional dense-graded pavements because of the amount of site work required to construct the stone reservoir under the pavement. Some costs can be off-set through a reduction of treatment methods that would otherwise be required for the stormwater runoff generated with conventional impervious pavement surfaces.

Porous pavements can be constructed using either asphalt or concrete materials or in some cases, placed pavers. This study concentrates on porous pavements constructed using asphalt. The use of porous asphalt pavements has become more common in recent years as the requirements for stormwater runoff have become more stringent.

Porous asphalt pavements are typically used in parking lots and around facilities as an alternative to placing impermeable or dense-graded asphalt surfaces. Their use on mainline roadways has been very limited because the requirements needed to make them successful are site-specific and the cost to construct some large-scale structures make the use of porous pavements impractical. Typically, porous asphalt pavement surfaces have air voids in excess of 18% at the time of construction as compared to properly constructed, dense-graded asphalt pavements with air void contents in the 3%-8% air voids range. The high air void percentages of porous asphalt pavements tend to make them poor candidates for pavements that will be carrying heavy trucks and/or high traffic volumes. Part of the strength of dense-graded asphalt pavements comes from the packing of smaller particles between larger particles, in essence locking the particles together. That added strength does not exist in porous asphalt surfaces. In order to meet the void level requirements, the amount of sand and finer aggregates is limited in comparison to dense-graded asphalt pavements.

Problem Statement

Porous asphalt pavement, when produced and placed correctly, can reduce stormwater runoff and increase the quality of the stormwater runoff. Currently, there is no standard specification for the production and placement of porous pavement in Connecticut. With no central guidance, this leads to duplication of effort and potential difficulties as different specifications are developed for each individual project. While porous pavement requirements are more site-specific than typical dense-graded pavement structures, a central specification related to the requirements for all porous asphalt pavements needs to be developed to streamline the process.

Objectives

The objective of this study is the development of a production and placement specification for porous asphalt pavement. It is intended also to provide design guidelines regarding what conditions are appropriate for this type of pavement. Specifically, this includes guidelines for the design of the porous asphalt pavement, a stone reservoir under the pavement, and inspection and maintenance requirements for the porous pavement surface.

Work Plan

The first part of the work plan was to review and summarize pertinent literature, including any production and construction specifications that lend themselves to aid in this specification development.

Once a summary of the reviewed literature was drafted, the research team conducted interviews with asphalt pavement producers/contractors to gain insights as to what their capabilities are as far as the production and placement of these materials. This was an important component to the work, as many porous pavements have been constructed previously in Connecticut and many of the producers already have successful experience with them. In addition to the information gained from the review of other agencies' specifications, it was deemed important to incorporate the existing successful practices of pavement producers for CTDOT. Following the collection of information through literature and specification review and stakeholder interviews, a porous pavement structure (PPS) specification was drafted which includes requirements for the stone reservoir under the pavement.

Review of Literature and Specifications

Porous Asphalt Pavements with Stone Reservoirs (FHWA)

Porous asphalt pavements with stone recharge beds are described in a Federal Highway Administration (FHWA) Tech Brief published in 2015 [1]. This is identified as a low-impact development (LID) technology with the potential for reducing environmental impacts. When properly designed and installed, porous asphalt pavements can provide environmentally-friendly and cost-effective means for managing stormwater runoff. The United States Environmental Protection Agency (EPA) thus recognizes the use of porous asphalt pavements as a best practice.

The differences between traditional dense-graded and porous asphalt structures begins with the preparation of the subgrade. For dense-graded asphalt structures, the primary function of the subgrade is to be unyielding; therefore, it is subjected to compaction. Conversely, the function of the subgrade associated with porous asphalt pavements is to facilitate the infiltration of water into the underlying soil. As such, the subgrade is not compacted for porous pavement construction.

Following the preparation of the subgrade for the porous asphalt structures, the FHWA Tech Brief recommends a geotextile fabric be placed over the uncompacted materials to prevent the migration of fines upward into the overlying stone recharge bed. The stone recharge bed material consists of clean, crushed stone with 40% voids to serve as temporary water storage. The stone recharge bed also serves as a structural layer supporting the layer(s) above. The next layer placed over the stone recharge bed serves as a stabilizing layer. This is called the “choker” or “stabilizing” course and normally consists of single-sized, smaller (relative to the stone in the recharge bed) stone that provides a stable and even layer on which to place the wearing surface. The porous asphalt layer(s) are constructed on top of the choker course. These asphalt layers have voids that are interconnected such that water will pass/drain through to the underlying stone recharge bed. The porous asphalt wearing surfaces typically have air void levels between 16% and 22%.

Of the many stated benefits to utilizing porous asphalt pavements, stormwater management is emphasized. As the stone recharge bed holds stormwater while it slowly recharges the ground, there is a reduction in stormwater runoff. Contaminants are also (at least partially) filtered out through the many permeable layers which, in turn, has the potential to improve water quality. In addition, the FHWA Tech Brief states that the New Hampshire Stormwater Center reports a 75% or greater reduction in deicing salts for maintaining the pavement during the winter months since water does not stand on the pavement surface and freeze/refreeze.

The FHWA Tech Brief does cite two significant issues that must be considered when deciding to use porous pavements. Most porous pavement applications are designed for light traffic loading only, such as would be encountered in a parking area used primarily for light vehicles, since the high void ratios can reduce the pavement’s strength. The second issue revolves around the site-specific conditions where the pavement is being proposed for use. These include the permeability of the soils as well as existing grades in excess of 5%. Conditions such as these may restrict the use of porous pavement, or require additional site work. Placement of porous pavements where there are buried utilities are also noted in the FHWA Tech Brief to complicate construction and design. This would require additional design and construction considerations unless the buried utilities in question exist below the depth of the structure.

Although there are noted exceptions, porous asphalt pavements are typically used for parking areas and other low traffic areas such as bike lanes, pedestrian walkways, driveways and shoulders. The FHWA Tech Brief states that there have also been successful implementations of porous asphalt on urban highways and streets.

There are significant site considerations that need to be addressed during the design phase of porous asphalt pavements. The slope for parking areas should be no greater than 5%, and if this is not achievable, then terraced parking lots with separating berms are recommended. The recommended range of soil infiltration rate is between 0.1 and 10 inches per hour, with 0.5 inches per hour recommended by the EPA. To achieve the necessary reservoir capacity and to avoid freeze issues in cold weather climates, the FHWA Tech Brief recommends a minimum depth to bedrock or to the seasonal high-water table should be at least 2 feet [1]. The FHWA Tech Brief cites the University of New Hampshire's recommendation that the bottom of the stone reservoir be at least 60% of the frost depth for the project location [1].

Hydrological design of porous pavements should be performed by a licensed engineer. This design determines the necessary porous pavement layer thicknesses that will store, drain and recharge stormwater from the pavement surface as well as from any surfaces adjacent to the structure that will add to the runoff volume. Figure 1 from the FHWA Tech Brief [1] demonstrates a couple of methods for designing for water overflow situations.

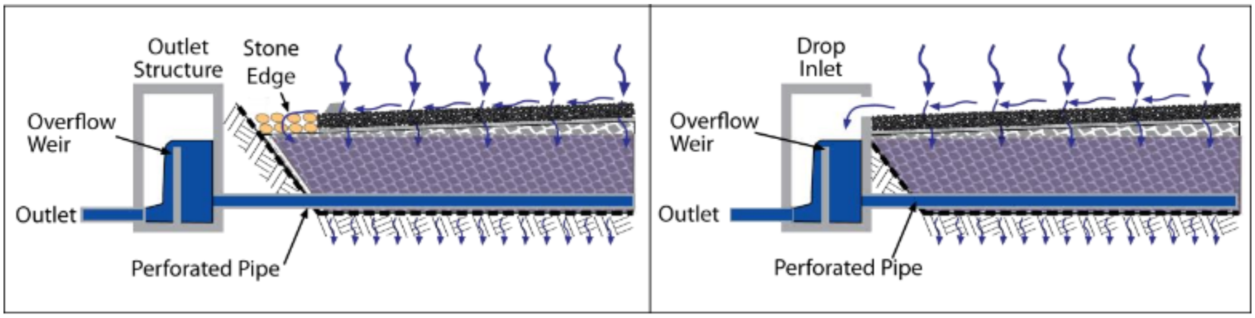

Image Courtesy Federal Highway Administration. 2015

Figure 1. Stone Edge Design and Drop Inlet Design for Water Overflow

The intention of the stone edge design in the left diagram of Figure 1 is that overflow will run to the stone edge of the pavement and drain into the structure, which contains a perforated drain pipe at the bottom, then through an outlet if necessary. The intention of the drop inlet design in the right diagram of Figure 1 is that the overflow will run directly into a discharge or outlet. In both cases, the perforated drainpipe at the bottom of the structure is intended to accommodate excess water that will not be infiltrated into the ground, either due to inadequate reservoir thickness during extreme events, a desire to limit amount of infiltration, or for a condition where the sub-grade soil is permeability has decreased.

The structural portion of the porous asphalt pavement design involves consideration of the loading that the structure is intended to carry. It is stated that for light automobile traffic, the structural requirements are insignificant and layer thicknesses are controlled by the hydrological design requirements for the stone reservoir with minimum pavement thicknesses of 2.5 inches [1]. If truck traffic is expected, the FHWA Tech Brief recommends that the porous pavement design should follow the AASHTO 93 design protocols using structural coefficients of 0.40-0.42 [1] for the porous asphalt layer.

The asphalt layers in a porous pavement design typically require a polymer-modified binder to reduce scuffing from tires at the surface and to minimize or avoid draindown. When the Marshall Mix Design method is used, 35 blows of the Marshall hammer per side are applied and, if SuperPave design procedures are used, then the number of gyrations is 50. It is also recommended that an anti-stripping agent be used if the producer of the porous asphalt pavement would be required to use an anti-stripping agent in a dense graded mix utilizing the same asphalt binder and aggregates. The stated mix property requirements include air voids in excess of 16% and a draindown of 0.3% or less.

The FHWA Tech Brief also offers guidelines that should be followed during the construction process. Among these are:

- Temporary control of stormwater around the site during construction to minimize the intrusion of fines.
- Subgrade soil should be excavated utilizing equipment with either tracks or oversized tires to distribute the load over a broader area to minimize the degree of compaction that would result in a reduced subgrade permeability and infiltration rate.
- Stone for the recharge bed should be placed in 8- to 12-inch layers with tracked equipment and rolled with one pass of a lightweight roller or a vibrating plate compactor.
- The choker/stabilizer course should be placed at a thickness of approximately one inch.
- Placement of the asphalt layers should be done with track pavers to distribute the load over a broader area.

- State or national guidelines for the placement of porous asphalt mixes should be utilized for the placement of the top course(s) and those layers should be compacted with two to four passes of a 10-ton non-vibratory roller.

UNHSC Design Specifications for Porous Asphalt Pavement and Infiltration Beds

The University of New Hampshire Stormwater Center (UNHSC) maintains a specification [2] for the design and installation of porous asphalt pavement structures. This specification is intended for use in a cold climate which lends itself well as a reference for the development of a specification for use in Connecticut.

Part 1 of the specification describes the information that needs to be submitted with respect to the material properties. These include manufacturer certifications of various materials that may be used in the construction of the porous pavement structure. This section also emphasizes the use of proper quality assurance measures with respect to the selection of personnel that will carry out the work. It is stated that any and all applicable standards with respect to construction methods, materials and workmanship shall be adhered to. These include any New Hampshire Department of Transportation (NHDOT), ASTM or AASHTO standards that may apply. Site assessment and construction phasing in this specification refer the user to the *Design Construction and Maintenance Guide* [3], produced by the National Asphalt Paving Association (NAPA), which is discussed in the next section of this literature review.

Part 1 of the UNHSC specification also contains requirements that outline the protection of existing infrastructure both onsite and adjacent to the site. Proper erosion and settlement controls, as well as the restoration of any damaged area(s) resulting from construction, are emphasized. Adherences to required traffic control measures are stated, as are weather limitations. It is stated that asphalt placement generally does not occur between November 15 and March 15 in cold climates. It is recommended that a contractor not proceed with the placement of porous asphalt structures when the ambient air temperature in the shade is below 60º F, when the ground temperature on site is below 50º F, when it is raining, and/or when rain is forecast for the day. Only the Design Engineer may adjust these requirements.

Part 2 of the UNHSC specification covers materials and specifies thicknesses of the different layers within the structure. The first part of this section is concerned with the materials in the infiltration bed, while the second part addresses the materials in the porous asphalt mix itself. The layers are shown graphically in Figure 2, which is from UNHSC [2].

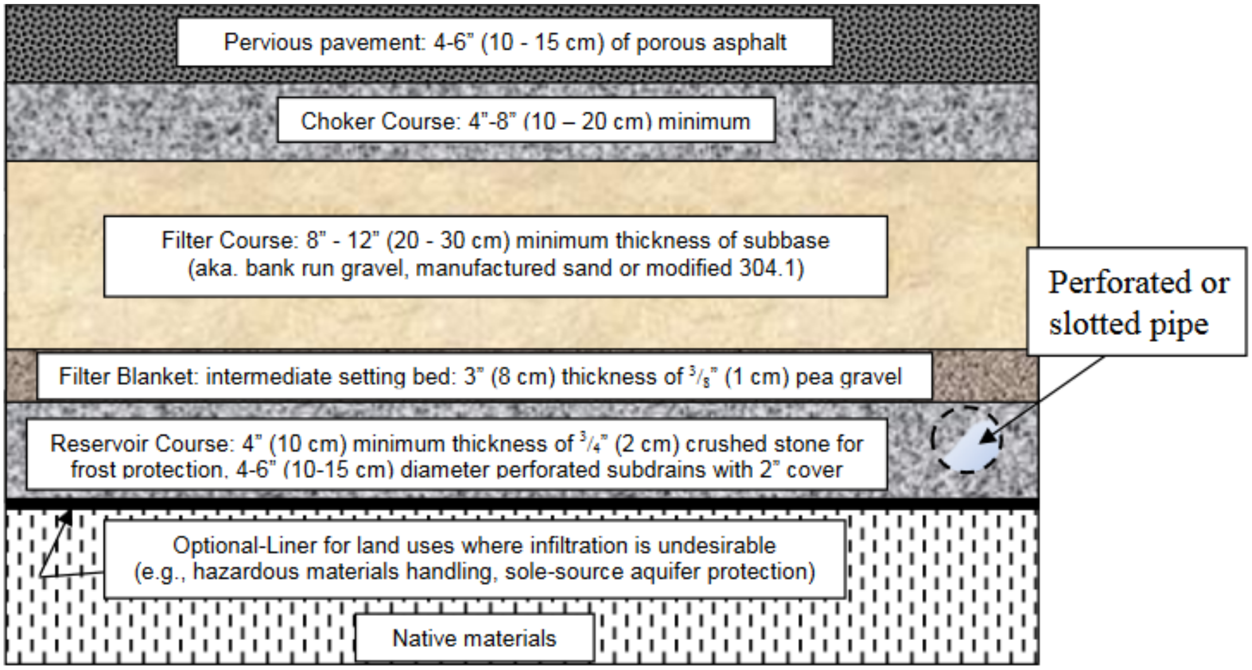

***Image Courtesy UNHSC**

Figure 2. UNHSC Pervious Pavement System Cross Section

Porous Media Infiltration Beds

According to UNHSC [2], the choker course material and the reservoir material are required to consist of clean crushed stone meeting the following requirements:

- Washed loss ≤ 0.5%
- Durability Index ≥ 35
- Abrasion Loss ≤ 10% for 100 revolutions
- Abrasion Loss ≤ 50% for 500 revolutions
- Choker Course Gradation meets AASHTO No. 57 (Engineer may approve No. 3 if No. 57 cannot be met)
- Reservoir Course Gradation meets AASHTO No. 3 (Engineer may approve No. 5 if No. 3 cannot be met.)

The reservoir course thickness depends on numerous varying criteria. The minimum thickness for the reservoir course is stated at 4 inches to act as a frost heave barrier, and also at 4 inches if the underlying materials are well-drained. If sub-drains are installed, then the minimum thickness is 8 inches. Sub-drains are stated as desirable any time infiltration of the stormwater is undesirable or anytime the native soil underneath the reservoir course is not sufficiently permeable.

Examples are provided by UNHSC for subbase thickness design based upon capacity, as well as a depth design consideration for frost. The necessary depth of the subbase is stated as the design storm precipitation (inches) divided by the reservoir course void capacity percentage.

For frost consideration, the total depth of the structure (surface to uncompacted soil) is a minimum of 65% of the local design frost depth.

An optional impermeable bottom liner is specified for use when infiltration of the stormwater runoff is to be prevented. Use of permeable geotextile liners and\or filter fabrics beneath the stone reservoir are discouraged when infiltration is intended. It is stated that these materials have been known to clog. It is recommended to use graded stone filter layers in lieu of geotextile layers (see Figure 2). Geotextiles are only recommended for use at the sides of the structure, if necessary.

The material for the filter course is required to have a hydraulic conductivity of 10 to 60 feet per day when compacted to 95%. The user is cautioned against over-compaction which will result in lower infiltration. In order to properly select the gradation of the filter course material, it is suggested to use a model that relates gradation to permeability. It is further suggested that ASTM D5084 test method be used to measure and report the hydraulic conductivity.

The filter blanket (see Figure 2) material is suggested to be of a gradation between the finer filter course material above and the coarser stone reservoir below. Pea gravel that is 3/8” is stated to be commonly used for this purpose.

Porous Asphalt Mix

The materials used in the porous asphalt layer(s) align with the standards in NAPA IS-115 and IS-131, which are discussed in the next section(s) of this literature review. The performance graded asphalt binder (PGAB) is suggested to be two performance grades stiffer than what would be required for a dense graded mix for the same application.

The specification allows two types of PGAB modifiers, styrene butadiene styrene (SBS) or styrene butadiene rubber (SBR). When fibers are added to the PGAB, it shall be at a dosage of 1.5% of the total volume of the mix. The PGAB is also required to meet AASHTO M320 standard. There are three mix designs which are recommended for use in this specification with respect to the PGAB. They are:

- PG 64-28 with 5 pounds of fibers per ton of mix
- Post-blended PG 64-28 SBR (to effectively obtain PG 76-22) at 1.5%, by volume, with 5 pounds of fibers per ton of mix
- Pre-blended PG 76-28 SBS

The PG 76-28 SBS is stated to have been successfully used in New England in recent years and is suggested where heavy wheel loading and higher traffic is anticipated. A table of listed Quality Control (QC) requirements is given in the event post-blended SBR or SBS is used. The table lists both mechanical as well as process controls and documentation.

Anti-stripping mix additives are required if the measured tensile strength ratio for the porous asphalt material is less than 80%. The additive used is based on the binder manufacturer's recommendation and is to be approved by the Design Engineer.

Fibers can be added to the mix if the draindown requirement of less than 0.3% cannot be met. When fibers are added, the air void requirement of the mix must still be met.

Coarse aggregate is defined as the portion of the aggregate that is retained above the #8 screen. Coarse aggregate requirements for use in the porous mix include:

- L.A. Abrasion ≤ 40%
- ≥ 75% of material coarser than # 4 maintain at least 2 fractured faces
- ≥ 90% of material coarser than # 4 maintain at least 1 fractured face
- ≤ 8.0% flat or elongated particles at a ratio of 3:1

Fine aggregate (defined as those particles passing the # 8 screen), must be durable, and free of injurious foreign material to the point that the material within the fine aggregate that passes the # 40 screen is specified to have a plasticity index of no more than 6.

It is noted by UNHSC in [2] that reclaimed asphalt pavement (RAP) may be used either in place of, or as an addition to, the fine aggregate in the porous mix. RAP is not allowed to constitute more than 10% by weight of the mix.

The mix design must be submitted by the contractor a minimum of 10 working days prior to the production of the mix. Samples of all materials used must be made available and certification must be submitted along with the PGAB. All technicians used for testing must be certified by the North East Transportation Training and Certification Program (NETTCP).

The mix design aligns closely with standards set forth in NAPA IS-131 (discussed later) however bulk specific gravity may not be determined using AASHTO T 166 as this test method is not intended for use with mixes that contain high air voids.

The mix design criteria are shown in Table 1 which is taken directly from the UNHSC Specification [2].

Table 1. UNHSC Porous Asphalt Mix Design Criteria

Sieve Size (inch/mm)	Percent Passing (%)
0.75/19	100
0.50/12.5	85-100
0.375/9.5	55-75
No.4/4.75	10-25
No.8/2.36	5-12
No.200/0.075 (#200)	2-4
Binder Content (AASHTO T164)	5.8 - 6.5%
Air Void Content (ASTM D6752)	16.0-22.0%
Draindown (ASTM D6390)*	$\leq$ 0.3 %
Retained Tensile Strength (AASHTO 283)**	$\geq$ 80 %
Cantabro abrasion test on unaged samples	$\leq$ 20%
Cantabro abrasion test on 7 day aged samples	$\leq$ 30%

* Either method is acceptable
**Cellulose, mineral, or polyester fibers may be used to reduce draindown.
***If the TSR (retained tensile strength) values fall below 80% when tested per NAPA IS 131 (with a single freeze thaw cycle rather than 5), then in Step 4, the contractor shall employ an antistrip additive, such as hydrated lime (ASTM C977) or a fatty amine, to raise the TSR value above 80%.

After the requirements for the preparation of aggregates and binder and proper mixture at the plant during production are met, the UNHSC specification details the requirements for QC during production. It is stated that standard QC testing may not be feasible when small quantities of mix are being produced and that the Design Engineer reserves the right to alter the QC plan based upon what is feasible.

The producer must employ a QC technician to perform the QC testing. The technician must have a valid HMA Plant Technician certification. The required QC/Quality Assurance (QA) testing and frequencies are shown in Table 2 which was taken directly from the UNHSC specification [2]. The tolerances for the required QC testing are shown in Table 3, which was also taken directly from the UNHSC specification [2].

Table 2. UNHSC QC/QA Testing Requirements for Porous Asphalt Production

Test	Min. Frequency	Test Method
Temperature in truck at plant	6 times per day	
Gradation	Greater of either (a) 1 per 500 tons, (b) 2 per day, or (c) 3 per job	AASHTO T30
Binder Content	Greater of either (a) 1 per 500 tons, (b) 2 per day, or (c) 3 per job	AASHTO T164
Air Void Content	Greater of either (a) 1 per 500 tons, (b) 2 per day, or (c) 3 per job	ASTM D6752
Binder Draindown	Greater of either (a) 1 per 500 tons, (b) 1 per day, or (c) 1 per job	ASTM D6390

***Table Courtesy UNHSC**

Table 3. UNHSC QC/QA Testing Tolerances

Sieve Size (inch/mm)	Percent Passing
0.75/19	-
0.5/12.5	± 6.0
0.375/9.5	± 6.0
0.187/4.75	± 5.0
0.093/2.36	± 4.0
0.0029/0.075	± 2.0
% PGAB	± 0.3

***Table Courtesy UNHSC**

Based upon results of QC/QA testing, the Engineer reserves the right to stop production and\or reject loads of material.

Execution and Installation

Before construction is allowed to begin, the Engineer must be notified for review and consent of final stake lines. Final surfaces must be free of roller marks and low spots. The tolerance for excavation elevations is ± 0.1 feet. The Engineer reserves the right, based upon testing and inspection, to require additional work and testing if deemed necessary. It is stated that the preferred watershed to porous pavement surface area ratio is 1:1.

Compaction of the native subgrade or significant construction traffic exposed to the native subgrade is not allowed unless infiltration is not intended such as with use of an impermeable liner. Collection of fine materials at the base of the excavation or puddles of water as a result of rain events and/or erosion must be removed and a minimum of a 6 inch scarification of the remaining subgrade surface is required. For parking lots, the top of the uncompacted subgrade must be level, which is the most suitable for uniform infiltration.

If necessary, and as determined through design calculations, perforated drainage pipes may be installed to move stormwater to an alternate discharge point. This would be the case with insufficient infiltration into surrounding soil due to insufficient permeability.

If a side slope geotextile is being used, it must be placed immediately after the subgrade preparation is completed. Adjacent strips of side slope geotextiles must overlap by at least 16 inches. The fabric must be placed and extended at least 4 feet outside of the excavation. The side slope geotextiles (if used), must be folded back over the edges to prevent the native material from washing out at the edges of the stone bed immediately after the placement of the aggregates in the bed.

Coarse aggregate layers must be installed to the appropriate grade and compacted in lifts not exceeding 8 inches.

The choker course must be installed in a manner that allows even and smooth placement of the pavement layer(s). The UNHSC choker course thickness is specified to be placed in layers not less than four inches thick.

QA/QC requirements for the installation for the porous aggregate layers include notifying the Engineer 24 hours prior to the start of work. The Engineer must also be notified for approval after the preparation of the subgrade, before the construction of the porous aggregate layers, after the filter course placement, prior to the placement of the choker course and prior to the placement of the pavement.

Haul units must be covered when transporting the porous asphalt mix and should be sprayed down with an appropriate release agent prior to loading. Dusting of the haul unit body is not permitted.

Paving units need to be in good working shape and have functioning automatic controls. Track pavers are stated to have been used most successfully when compared to others.

Rollers are also required to be in good working shape and are required to have static weights between 8 and 12 tons. Rubber tired rollers are not required.

All surfaces that will contact the asphalt mix (e.g., utility structures) are required to be covered with an asphalt emulsion immediately prior to placement.

The mix must be discharged from the haul unit at a temperature between 275º and 325º F and within 10º F of the compaction temperature for the mix design.

It is recommended to place the wearing surface in two lifts between 1.5 and 2 inches each in order to obtain uniform compaction. It is suggested that the first layer cool to 100º F prior to the placement of the second layer in order to allow for sufficient set time.

The layer(s) must be compacted immediately using the rollers. The compaction target is 16% to 19% air voids as measured using a vacuum sealing methodology. Breakdown rolling must occur when the mix is between 275º F and 325º F. Finish rolling takes place between 150º F and 200º F. In areas that are inaccessible to the large rollers, smaller compaction equipment is permitted. Finish rolling takes place until all of the roller marks have been removed.

Transverse joints must be cut vertical to the plane of the pavement, perpendicular to the centerline and must be coated with an emulsion. Longitudinal joints that have cooled significantly must also be coated with an emulsion. The Engineer may require the longitudinal joints be cut back to a sufficient vertical edge. The pavement surface on either side of a longitudinal joint must be within 3/8-inch of each other or it must be removed and replaced.

The tolerances and suggested testing schedule for placement of the porous HMA surface is shown in Table 4 which was taken directly from the UNHSC specification.

Table 4. UNHSC QC/QA Requirements During Paving

Activity	Schedule/Frequency	Tolerance
Inspect truck beds for pooling (draindown)	every truck	NA
Take temp of asphalt in truck	every truck	> 135°C (275°F)
Take temp of PA mix in the paver	each pull	within 6°C (10°F) of the recommended compaction temp
Consult with engineer to determine locations of butt joints	As needed	NA
Test surface smoothness and positive drainage with a 10' straightedge	after compaction	9.5 mm (3/8")
Consult with engineer to mark core locations	after compaction	NA
House test with at least 5 gpm water	after compaction	immediate infiltration, no puddling

***Image Courtesy UNHSC**

In the event that the asphalt layer(s) of a porous pavement needs to be resurfaced, the recommendation is that the older pavement be milled and resurfacing take place over the choker course. Applying tack coat to the existing pavement and paving over it is not recommended.

Porous Asphalt Pavements for Stormwater Management Design, Construction and Maintenance Guide (NAPA IS-131)

The NAPA Guide (Information Series) IS-131 [3] states that porous asphalt pavements provide public works officials and site planners the option to manage stormwater in a manner that is environmentally friendly. Because of this, these pavements are reportedly in demand.

NAPA states that the structure consists of the following from bottom to top:

- An uncompacted subgrade for infiltration into the soil
- A geotextile fabric over the top of the uncompacted subgrade
- A coarse aggregate stone recharge bed with 40% air voids
- A choker or stabilizer course
- A porous asphalt surface with interconnected voids

Design

Of note in the general guidelines for design in NAPA [3] are the following:

- Infiltration rates of 0.1 to 10 inches/hour are stated to work best for porous structures.
- There should be no less than 2 feet of depth to bedrock or the seasonal high water table from the bottom of the stone reservoir.
- The bottom of the infiltration bed should be flat for maximum infiltration.
- Terraced sections with berms between them should be used when the porous surface slope exceeds 5%.
- The impervious to pervious surface area ratio on site should be no greater than 5:1.
- There should be an alternate route for the stormwater to reach the recharge bed in case the surface is plugged or cannot drain stormwater into the media fast enough.
- An overflow system should be provided.
- The recharge bed should drain in no more than 12 to 72 hours.

NAPA recommends reviewing hydrologic soil groups (as maintained by the Natural Resources Conservation Service (NRCS) [4]) as a good starting point during design. The NRCS classifies 4 different soil types according to their hydraulic conductivity at different depths. Hydrologic Soil Groups A and B are suggested as the most ideal for porous pavement locations as they have the highest levels of hydraulic conductivity.

It is also suggested to look into possibilities of utilizing the porous pavement to infiltrate water from other impervious areas on site. Because most recharge beds are typically designed to handle and store more than typical storm volumes, there may be opportunities to reduce runoff beyond that of the surface of the porous structure. If additional runoff is intended to be channeled into the porous pavement structure, consideration should be given to the source of the extra runoff to determine whether any pretreatment such as sedimentation or filtration of sand may be required.

Hydrologic Design

IS-131 [3] states that the hydrologic design elements of the porous structure should be carried out by a licensed engineer who is skilled in hydrology.

Structural Design

It is stated that the vast majority of constructed and evaluated porous pavement structures were designed only to carry light traffic loads. It is noted, however, that *"…many porous pavements have served their traffic supporting needs for over 20 years."* [3]

The guide [3] gives minimum recommended thicknesses of the porous asphalt layer(s) based upon the possibility of higher traffic loading. The minimum thicknesses stated are as follows:

- Parking – 2.5 inches
- Residential Street – 4.0 inches
- Heavy Truck – 6.0 inches

Soil Investigation

Investigation of the soil involves digging test pits six to eight feet in depth. Soil conditions should be observed and recorded. These conditions include color patterns, depth to bedrock, depth to the water table, depth to hardpan and estimated coarse fragments. Soil infiltration rates should be measured as closely as possible to the bottom depth of the stone reservoir. It is stated that most references indicate that the infiltration rate be no less than 0.5 in/hr, while others indicate that soils with infiltration rates less than 0.25 in/hr are not suitable for porous pavement applications without significant modification. The guide goes on to state that although these rates are most commonly cited, there have been successfully placed porous structures over soils with rates as low as 0.1 in/hr.

Materials

NAPA states in [3] that geotextile fabrics are typically used to prevent the subgrade fines from migrating upward into the stone media. An example specification for this type of material is given. The requirements for the geotextile material in that example include:

- Grab tensile strength ≥ 120 lbs (ASTM-D4632)
- Mullen Burst Strength ≥ 225 psi (ASTM-D3786)
- Flow Rate ≥ 95 gal/min/ft^2 (ASTM-D4491)
- UV Resistance after 500 hrs ≥ 70% (ASTM-D4355)

Gradation and void suggestions for the stone recharge bed and for the choker course are similar to those stated by UNHSC [2]. It is also states that the choker course should be not more than one inch thick. It is further stated that a number of contractors have successfully constructed porous pavement structures without the use of a choker course and as such, so NAPA considers the choker course as optional.

The statements made regarding the porous asphalt materials align with those suggested by UNHSC [2]. Reference is given to NAPA IS-115, *Design, Construction* *and Maintenance of Open-Graded Asphalt Friction Course* [5]. It is suggested to ensure the following with the use of porous asphalt layer over the porous structure:

- Minimum of 16% air voids
- Minimum of 5.75% asphalt content for typical 3/8" nominal mixes
- Maximum of 0.3% draindown
- Anti-stripping agent if required for dense mixes utilizing the same materials

Nominal open-graded mix sizes are also suggested along with thickness ranges for different applications. They include:

- ⅜" parking/recreational facilities. 1.5 – 3.5 inch thickness
- ½" for wearing surface, streets, heavy commercial. 2.0 – 4.0 inch thickness
- ¾" for wearing surface, roads and heavy commercial. 3.0 – 6.0-inch thickness

Post Construction and Maintenance

After construction is complete and the site is stabilized, any temporary stormwater control measures should be removed. Permanent signs may be posted at the site to keep maintenance personnel aware of the porous pavement. This may help to ensure that abrasives are not used during winter maintenance operations and to make sure the pavement is not seal-coated. It is suggested that the porous pavement be inspected often during the early life of the structure, and at least once per year after that. Inspections should take place after large precipitation events to check for ponding of water. It is recommended that the porous pavement be vacuum-swept twice per year to help prevent issues with clogging. It is stated that damage to the pavement may be repaired using dense graded mix/materials so long as the repaired surface area is less than 10 % of the total surface area of the structure.

Oregon State University Extension Service Stormwater Solutions

Oregon State University (OSU) Extension Service hosts porous pavement information, video tutorials, fact sheets and an interactive hydrologic calculator on their website [5].

The calculator is in the form of a spreadsheet that is downloadable via the referenced website. The calculator is useful for estimating the required thickness of the stone recharge bed. It considers all of the elements required to calculate whether or not the porous structure will drain the input stormwater in both 30 and 72 hours, and generates a hydrograph for the input storm. The user inputs the following information:

- 24-hour rainfall total
- Stormwater collection surface area
- Stone reservoir surface area
- Runoff coefficient
- Subgrade soil infiltration rate
- Recharge bed depth and void ratio
- Additional outflow location/depth

In addition to the calculated stormwater inflow and outflow rates, the outputs from the calculator include:

- Raw data that can be plotted as a hydrograph up to 72 hours (3 days)
- Maximum water depth in the stone reservoir
- Depth of water in the stone reservoir after 30 hours
- Has the reservoir drained after 30 hours? (yes/no)
- Has the reservoir drained after 72 hours? (yes/no)
- Total water storage capacity of the reservoir

Pervious Pavement Design Guidance (Caltrans)

A guidance document published by the California Department of Transportation (Caltrans) offers insight to project selection, design criteria, construction and maintenance of pervious pavements in California [6].

Pavement types are categorized according to their anticipated loading type and speed. An assessment is then given to that category of pavement to describe the type of risk that would be associated with constructing those pavements as pervious pavements. Category A consists of sidewalks and bike paths that have no vehicular access. These are stated to be pavements that will take on rainfall runoff from nearby impervious areas. Loading and speed are not a consideration as there is no vehicular access and as such, Category A pavements are considered low risk for pervious pavement. Category B consists of parking lots, access roads for maintenance vehicles and sidewalks and bike paths that have vehicular access. They are intended to carry few heavy loads and traffic speeds less than 30 miles per hour. Category B facilities are also considered low risk for pervious pavements. Category C consists of rest areas and maintenance stations. They are intended to carry a moderate volume of heavy loads and are intended for low speeds. Category C facilities are also considered low risk options for pervious pavements. Category D consists of shoulders, select low volume roads and areas adjacent to noise barriers. Category D facilities are intended for moderate volumes of heavy loads at high speeds and as such are considered medium risk facilities for pervious pavement applications. Category E consists of highways and weigh stations carrying high volumes of heavy loads at high speeds. Category E facilities are considered high risk for pervious pavement applications. In summary, at the time of the publication (August 2014), three of the five pavement categories were listed as low risk considerations for pervious pavements. They are Categories A, B and C.

It is stated that the Caltrans National Pollutant Discharge Elimination System (NPDES) permit through the EPA requires the department to consider LID strategies on their projects. LID strategies (relative to stormwater) are defined as practices that treat the stormwater onsite as opposed to collecting and routing the water to stormwater facilities. This is accomplished through design methods that collect, filter, store, evaporate, detain and infiltrate the stormwater where it is collected.

The best soil types for considering an infiltration type system are stated as Hydrologic Soil Groups A and/or B from the NRCS [4]. It is further stated that other soil types may be considered, as the final determination will be dependent upon the infiltration rate and drawdown time requirements. Among citing criteria, it is suggested not to consider pervious pavements where landscaped areas will drain into the structure (debris and sediment could cause clogging), where pavement will be immediately adjacent to structural foundations, where maintenance (i.e., vacuuming) of the pervious structure is not feasible and where sanding for winter maintenance will take place.

Cost considerations include contacting supplier organizations to ensure that planned/estimated costs reflect local material costs. It is also suggested to consider alternative designs that will accomplish that of the pervious structure, but to be cognizant of the possibility that a reduction in drainage construction items can realize a cost reduction with pervious pavements.

Rhode Island Stormwater Design and Installation Standards Manual

A Rhode Island stormwater design manual [10] provides key considerations for the use of *Permeable Paving.* From a feasibility perspective, the manual states the following requirements:

- Minimum soil infiltration rate of 0.5 inches per hour
- Soil < 20% clay
- Soil < 60% silt
- The pavement may not accept runoff with high potential pollutant loads unless the structure is lined with an impermeable liner
- The separation of the bottom of the structure from the groundwater table and bedrock must be at least 3 feet. This may be reduced to 2 feet for strictly residential land uses.
- The slope must not exceed 5.0%.
- The upstream vegetation is required to be completely stabilized prior to allowing any flow to the structure.

The manual indicates that the use of permeable pavements results in pollutant removal. A scale is used where the possible indicators are *good*, *fair* and *poor*. The listed pollutants are phosphorus, nitrogen, cadmium, copper, lead, zinc, coliform, Streptococci and E. coli. The manual grades the use of permeable pavements as *good* when it comes to the removal of the listed pollutants.

It is indicated that the void space in the surface course(s) may range from 10% to 25%.

The minimum amount of geotechnical testing for feasibility of a permeable pavement is one test hole location per 5,000 square feet of potential permeable surface. A minimum of one test is required for surfaces less than 5,000 square feet.

The manual indicates that due to clogging susceptibility, permeable pavement practices are not appropriate for high traffic areas where there will be in excess of 1,000 vehicle trips per day. It is also suggested that permeable pavements should only be constructed to handle precipitation that falls directly on the permeable surface and that run-off from adjacent impermeable surfaces should be minimized to reduce the risk of clogging.

The manual refers to general construction specifications that were developed by UNHSC [2].

Producer/Contractor Interviews

Porous pavements have been successfully produced and placed in Connecticut for many years. In the absence of a standard Connecticut specification, local pavement producers have developed their own successful mixes and placement methodologies that work for their facilities and materials. In addition to the information gained from reviewed literature in the development of a CTDOT specification, it was desired to incorporate and include the successful methodologies that have been utilized by the producers in Connecticut. Major producers for the CTDOT were contacted and forwarded a preliminary copy of a specification that was drafted by the research team based solely on reviewed literature. The research team then, both in person and over the phone, interviewed those producers to gain their input and experiences and incorporated elements of their success into the specification.

Producer/Contractor Interview Conclusions

- AASHTO No. 3 is the preferred stone reservoir gradation and is easily produced.
- AASHTO No. 6, No. 56 and No. 57 gradations are all reasonable for the choker course.
- The choker course should be no thicker than what is required to provide a stable and smooth paving surface.
- Flat and elongated specification ratio of 5:1 is reasonably achievable for AASHTO No. 3, No. 6, No. 56 and No.57 gradations.
- Hand work will be required any time haul units leave ruts over the stone reservoir or the choker course.
- Both SuperPave and Marshall designs have successfully been used by contractors for porous surfaces.
- Porous mixes with binder contents in excess of 4.5% to 5.0 % may be difficult to manufacture for some producers.
- Binder contents in the 4.0% to 4.5 % range have been used successfully when SBS modified binder is used in conjunction with fibers.
- Some producers do not stock polymer-modified binder at locations where porous mixes are produced due to the low quantity of mix involved with most porous pavement jobs.
- PG 64-22 binder in combination with fibers and RAP has been used successfully in porous mixes.
- Minimum liquid binder contents should not be specified given the range of successful designs used by contractors in the past.
- Minimum average film thickness as calculated by CTDOT Division of Materials Testing Form MAT412s is the best process for specifying liquid binder as porous/open mixes have a higher susceptibility to oxidation and aging.
- Tracked pavers should be required in order to distribute the paver weight over a larger area, as the layers will tend to move during construction.

- Signage of porous pavement structures is necessary to keep maintainers informed as to how the pavement should be treated (no sanding, no seal coating, no piling of mulch, etc.).

Liquid Asphalt Binder Requirement Determination

In light of the varying liquid asphalt binder requirements reviewed in the literature as well as discussed with producers, it was decided that binder film thickness would likely be the best method of control as opposed to a minimum liquid requirement. Although the developed specification does not refer to the porous asphalt layers as OGFC, there are many similarities between typical OGFC mixes and what is being proposed in this specification. Many of the agencies simply refer to their OGFC specifications for the porous asphalt surfaces in their PPS specifications. The primary concern is the open nature and high void content of the mix and the exposure to oxidizing/aging natural elements that it will be required to withstand.

FHWA Technical Advisory T 5040.31 [11] discusses design and use elements of OGFC with regard to asphalt binder film thicknesses on the aggregate particles. It is stated in the document that open graded mixes (which includes porous asphalt pavements) generally require a higher asphalt content to achieve greater asphalt film thicknesses as compared to dense graded mixes. The greater film thickness of asphalt helps to combat the effects of stripping and oxidation. Typical dense graded mixes require an average asphalt binder film thickness of 4 to 6 microns, while open graded mixes are then required to average asphalt binder film thicknesses of 8 to 11 microns to reduce damage from oxidation and water.

A report discussing the effect of binder film thickness on aging of asphalt binder [12] was developed by the National Center for Asphalt Technology (NCAT). In order to provide mixture durability over the intended service life of asphalt, the objective of the NCAT research was to establish a threshold film thickness beyond which aging of the asphalt binder would be limited. A limiting factor to this research is that there was only one aggregate combination studied and the mix was a dense graded mix compacted to 8.0% air voids. The study found that mixes that had an asphalt binder film thickness of less than 9 to 10 microns were more likely to experience accelerated aging. Logically, it can be expected that mixes with void contents higher than 8.0% will experience more oxidation and aging from natural elements and therefore will require a thicker binder film thickness.

Check of Contractor Mixes

In addition to the reviewed binder film thickness literature (which is limited), the research team checked some collected mix designs from producers to gain insight as to what their average film thicknesses were. This was done by entering the required information from those mixes into CTDOT form MAT412s that is used for acceptance purposes at production facilities during production of HMA. The sheet calculates film thickness based upon the entered values from the mix. These required values are, among other items, gradation, aggregate specific gravities, absorption and binder content. It was observed that the lowest value of average binder film thicknesses for all of the mixes was 12.4 microns. This value is in excess of the stated required film thicknesses in both the FHWA and NCAT documents [11], [12].

Summary of Findings

Porous pavement structures have been used successfully in Connecticut and across the United States for several years. Porous asphalt pavements differ from typically constructed dense graded pavements as they are normally built over an uncompacted subgrade which facilitates infiltration of the water into the underlying soil. Caltrans [7], for instance, has identified the use of permeable pavements for a number of applications, such as sidewalks, bicycle paths, parking lots, access roads for maintenance vehicles and rest areas.

Literature reviewed for this study found FHWA and EPA both stating that when properly designed and installed, porous asphalt pavements can provide environmentally friendly and cost effective means for managing stormwater runoff. Contaminants are also (at least partially) filtered out through the many permeable layers which, in turn, has the potential to improve water quality.

Durability when exposed to heavy traffic loading and the initial cost of construction are two commonly stated limitations to the use of porous pavements. Common to all of the literature that was reviewed for this report, are the serious considerations that need to be made for the appropriate use of a porous pavement structure for any given situation. These considerations include, but are not limited to, slope percentage, total storm water contribution area, total porous pavement surface area, traffic loading and soil infiltration capacity. The potential of clogging the porous surface during its service life is another concern that must be examined during design, and must be monitored via annual maintenance and inspection. For instance, UNHSC states that a measured surface infiltration rate of 10 inches per hour or less suggests that the pavement is near a clogged state.

Nearly all of the reviewed literature suggest that the thickness and storage capacity of the PPS layers be performed by an engineer who is fluent and skilled in hydrologic design. The specification that was developed during this research requires that a licensed engineer perform these calculations. Feasibility analyses and estimating may be assisted with the use of hydrologic calculators such as one made available by Oregon State University Extension Service [5]. However, while these tools are helpful estimators, the final determinations need to be made by a qualified person.

It is suggested in the literature (FHWA [1], NAPA [3] and Rhode Island [10]) that slopes in excess of 5.0% may be an inappropriate application for a porous pavement structure, or alternatively require terracing of sections of the structure. The research team decided that this limit would be appropriate for CTDOT applications, as well.

Water infiltration rates for the underlying subgrade soil are also discussed in all of the reviewed literature. In a convenient manner, soils can be categorized by their respective infiltration rates, as is done in the Natural Resources Conservation Service (NRCS) [4]. For the specification developed in this study, the research team took the approach used in NAPA [3], which allows PPS to be constructed over areas of only NRCS hydrologic soil groups A and B (which have the highest levels of hydraulic conductivity). This is a conservative approach that CTDOT might consider revising based upon future successful investigation of PPS constructed over areas of lower hydraulic conductivity than group A or B soils.

Within the literature reviewed, there are conflicting opinions regarding the use of geotextile fabrics to line the bottom of the excavation of the porous pavement structure prior to placement of the stone reservoir materials. The intention of the placement of the fabric is to prevent fines from migrating from the subgrade into the reservoir portion of the structure, which may ultimately result in clogging. UNHSC [2] states that these fabrics shouldn't be used as they themselves are prone to clogging. The research team recommends that porous pavement structures be used in locations with subgrade soils where the concern for the migration of fines into the bottom of the stone reservoir without the use of a geotextile is minimal. If there is a fear that the native underlying soil contains sufficient fine material such that clogging is a concern, then a porous pavement structure is likely not an appropriate application in that instance. It is also the opinion of the research team that porous pavement structures should be placed only in areas where the seasonal average high-water table does not reach the level of the bottom of the stone reservoir. This alleviates any concerns about upward migrating fine aggregates such as silts, clays and fine sands. The use of geotextiles to prevent the migration of fines laterally from the sides of the excavation for the porous pavement structure should be considered to prevent clogging of the stone bed. This will also prevent settlement of the areas surrounding the porous pavement structure with the migration of the fines. In any and all cases, the use of geotextile fabrics will be at the discretion of the Design Engineer or Project Engineer. Any time geotextile fabrics are used, they should be of the non-woven type.

The UNHSC specification states that the stone material in the reservoir layer meet the gradation requirements of AASHTO No.3 or AASHTO No. 5. If gradation No. 3 cannot be met, then No.5 may be approved by the Engineer. The research team also concurs with this requirement, as these gradations provide for adequate structural and water storage capacity. These are also standard gradations that most producers are familiar with and should be capable of producing.

The choker course gradation options of AASHTO No. 6, AASHTO No. 56 or AASHTO No. 57 were decided upon by the research team as they are slightly less coarse than the stone reservoir materials and, as such, should provide a stable and smooth layer for the porous asphalt layer(s), while still adequately draining stormwater through to the reservoir. The durability/quality requirements were selected to ensure the aggregates will not degrade during placement and compaction and to ensure adequate structural integrity of the layers.

As previously stated, final design calculations for the stone bed sizing need to be performed by a licensed engineer who is qualified to make the necessary hydrologic determinations. During the design, it may be determined that sub-drains need to be incorporated in order to address a case where a storm occurs which the porous pavement structure cannot accommodate, or as auxiliary drainage if the surface pavement becomes plugged. For this situation, standard drainage calculations and practices are recommended, and the designs illustrated in FHWA [1] may be considered.

The choker/stabilizer course is suggested to be between 4- and 8-inches thick by UNHSC [2], 1-inch thick by FHWA [1], and not more than 1-inch thick by NAPA [3]. The research team is in favor of a choker course that is placed at a thickness of no more than 1.5 inches. The reason for this is that the choker/stabilizer course simply needs to provide an adequate base layer for paving the surface, and an excessive thickness of this base layer reduces the overall conductive efficiency of the structure since it contains less void space than the stone reservoir. The research team is of the opinion that CTDOT could investigate the possible elimination of the choker/stabilizer layer in the future.

A general diagram showing the different layers and materials recommended for the CTDOT porous pavement structure specification is shown in Figure 3.

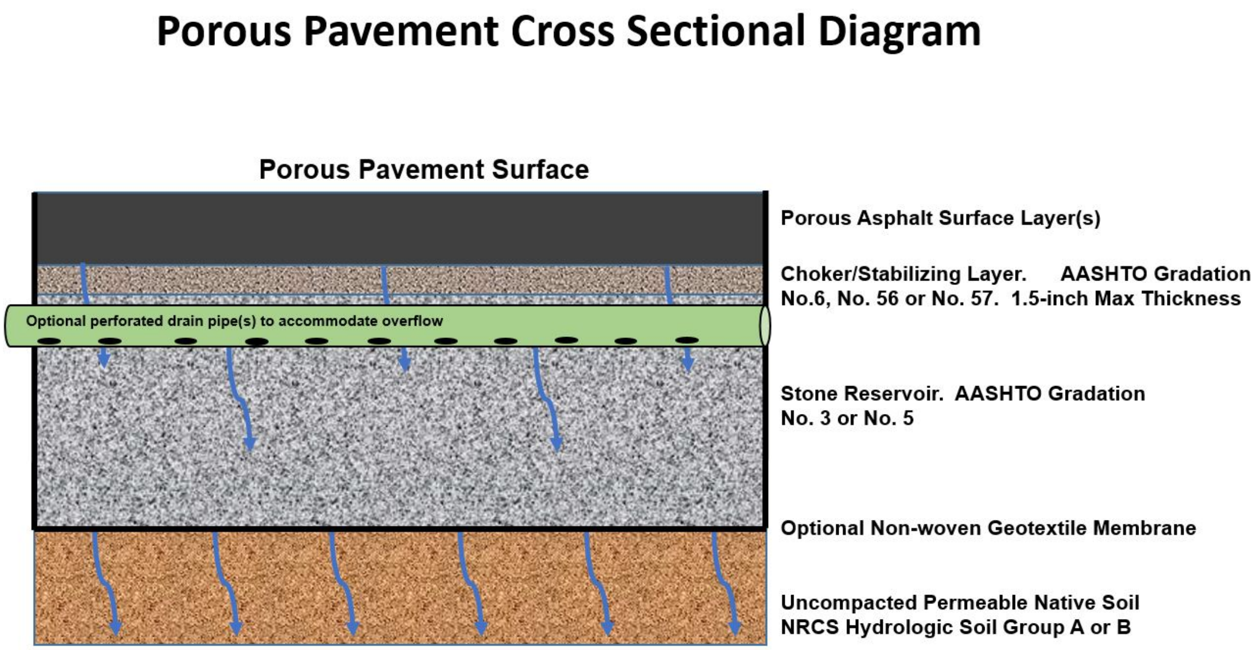

Figure 3. General PPS Layer Diagram

The selection of asphaltic materials specified for the porous layers is a combination of insight gained from literature and correspondence with HMA producers for CTDOT. FHWA [1] states that polymer-modified binders are "typically required" for porous pavement to reduce scuffing and reduce draindown potential. UNHSC [2] and NAPA [3] suggest a liquid binder that is two (2) grades stiffer than what would be required for a dense mix in the same climatic region. In Connecticut, that would mean a high-temperature performance grade of 76. SBS and SBR polymer and fibers are allowable additives. When the asphalt binder grade is not bumped two grades on the high temperature, then it is suggested that five pounds of fibers per ton of mix are added to increase the asphalt film thickness.

After discussions with HMA producers serving CTDOT, it was quickly realized that there has been a vast array of methods employed to create the porous asphalt surfaces.

Some included polymer-modified binder, some incorporated different types of fibers, and some used RAP to stiffen the virgin binder to achieve the desired mix. The HMA producers have been utilizing their version of porous mix successfully in the Connecticut region for some time.

Given the materials reviewed and what has been already successfully used by HMA producers, the research team chose to embrace all of those options for purposes of this specification development, provided the mix meets certain performance standards as indicated below. The only specific asphalt material selection requirement that was added is the addition of either polyester or nylon fibers to the mix when polymer-modified binder is not used. This will add to the strength and flexibility of the mix as well as counter draindown potential.

CTDOT has completely transitioned to the SuperPave HMA design system over the last two decades. There are, however, suggestions made for porous Marshall Mix Design methods by FHWA [1] and at least one interviewed HMA producer who has successfully utilized Marshall methods for porous asphalt mix designs. The research team also chose to embrace these options for this specification until, and unless, it is proven that the Marshall method is insufficient for these purposes. In an effort to provide the maximum liquid content, the research team recommends compactive efforts of 50 blows and 50 gyrations for the Marshall and SuperPave mixes, respectively. Given the possible large variation in mixture characteristics with the different designs, the research team decided that specifying a minimum asphalt content was not appropriate. Upon consideration of the binder film thicknesses for some of the mixes that were submitted by Connecticut HMA producers, as well as the findings presented by FHWA [11] and NCAT [12], the research team decided that a minimum binder film thickness of 12.0 microns is suitable. The research team used the CTDOT film thickness calculation method that appears on CTDOT acceptance form MAT412s.

Given the large potential variation in mixes and mix materials, the research team selected the following tests that the mix must be in compliance with to reach acceptable field performance:

- Resistance of Compacted Bituminous Mixture to Moisture Induced Damage
    - AASHTO T 283 (minimum 80%)

- Standard Method of Test for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures
  - AASHTO T 305 (maximum 0.3%)
- Cantabro Loss
  - Texas DOT Tex-245-F (maximum 35%)

The research team recommends a minimum QA sampling/testing frequency of once per 600 tons of produced material. Given the potential for projects with significantly lower tonnages than 600, it is also specified that there must be a minimum of one sample/test that takes place per project. This testing will ensure the proper air voids, binder film thickness, and gradation.

Conclusions and Recommendations

The research team developed a first draft version of a porous pavement specification based solely on reviewed literature and specifications from other agencies and organizations, such as the FHWA, NAPA and the University of New Hampshire Stormwater Center. This version was submitted to nearby asphalt pavement producers who routinely provide HMA to CTDOT for their review. Based upon discussions of their experiences, the first version of the specification was modified to incorporate the broad range of options that each unique producer has had success with in the past. The result of these reviews and discussions is the Draft Specification in Appendix A.

It is recommended that the performance of porous pavement structures with various combinations of materials as currently observed from CT HMA producers is monitored over time. Updates and modifications to the specification should emphasize materials and practices that are found to enhance the performance, durability and longevity of the structures. The specification should also be modified to exclude the use of materials and practices that are found to contribute to accelerated aging and failure of the structure.

Information on required asphalt binder film thickness on porous asphalt mixes is limited. It is recommended that the production film thickness of porous asphalt layers is monitored and tracked in an attempt to align these values with predicted and actual performance.

References

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Appendix A. Special Provision Guidance Document for Designers

SPECIAL PROVISION GUIDANCE DOCUMENT FOR DESIGNERS

Porous Pavement Structure (PPS)

Providing porous asphalt pavement structures (sometimes denoted as permeable pavements or pervious pavements) for parking lots, driveways, bikeways, sidewalks or shoulders is a means to reduce or eliminate, as well as to improve the quality of, stormwater runoff. Porous asphalt pavements allow storm water to penetrate completely through the asphalt pavement into a stone reservoir where the water can then percolate into the soil. Their use on mainline roadways has been very limited because of the customized requirements needed to make them work under heavy traffic loads.

1. Site Considerations

A. When a porous pavement structure (PPS) is being considered for use, the total land area contribution of stormwater to the site must first be determined. This determination is made from a hydrologic study that should be performed by a qualified engineer. The total contribution area consists of the PPS surface area and any contributing areas (roofs, sidewalks, impervious pavements, slopes that drain onto the PPS) that are adjacent to the intended PPS. If the ratio of contributing runoff area to PPS area is in excess of 4:1, PPS should not be used. (*Increasing this ratio should be considered, following its successful experimental use in the future in Connecticut*).

B. A PPS should not be used in areas where either the seasonal high water table or depth to solid bedrock is closer than 2 feet to the bottom of the excavation (infiltration bed).

C. A PPS is not recommended to be used on sites with grade slopes in excess of 5 percent. If used in conjunction with slopes greater than 5 percent, terracing the parking lot and separating the sections with impermeable berms should be included for design and construction.

2. Initial Evaluations

A. Soil classification and testing of hydraulic conductivity shall take place at selected on-site location intervals of approximately every 5,000 square feet following excavation test pits to the anticipated subgrade depth. These locations shall be at the discretion of the Engineer. A minimum of one test for hydraulic conductivity shall take place at any potential PPS site. The in-place hydraulic conductivity shall be measured in accordance with either ASTM D3385 or ASTM D5093. (*Selection of the best testing method should be in favor of the method that results in the lowest measured hydraulic conductivity*)

B. The hydraulic conductivity, as measured in section 2.A, shall be compared to those values in Tables 7-1 and 7-2 of Chapter 7 of Part 630 (Hydrology) in the National Engineering Handbook of the Natural Resources Conservation Service of the United States Department of Agriculture [S1]. If the measured hydraulic conductivity of the soil falls within the range specified for Hydrologic Soil Groups A or B, the site may be considered a candidate for a PPS. If the measured hydraulic conductivity falls into the range(s) of Hydrologic Soil Groups C or D then alternate structures should be considered for use first. (*This may be adjusted following successful experimentation of porous pavement structures over subgrade soils with lower hydraulic conductivity in Connecticut*)

C. The need for geotextile fabric over the subgrade and against the trench walls shall be determined. The use of geotextile fabrics shall depend upon the fines content and gradation of the fine aggregate in both the subgrade and surrounding soil, the seasonal average high water table and the risk of clogging the selected geotextile fabric. The use of geotextile fabrics to line porous pavement excavations shall be at the discretion of the engineer.

D. A design thickness calculator such as that provided by the Oregon State University Extension Service [S2] is recommended. Regardless, the final thickness determination of the aggregate layers, the total depth of the structure shall be not less than 70 percent of the frost depth for the site location. (E.g. a frost depth of 5 feet would require a minimum structure thickness of 3.5 feet.

E. When infiltration capacity is insufficient for the design storm, sub-drains shall be designed to accommodate the excess drainage to daylight or nearby adjacent stormwater facilities. This shall be done in accordance with standard drainage design practices.

3. Design of Underlying PPS Aggregate Layers

A. The final design thickness shall, as a minimum, take into consideration all of the following elements.

- Typical design storm rainfall depth
- Total stormwater collection surface area (including surrounding areas where drainage is directed to the PPS)
- Total stone recharge bed surface area
- Infiltration rate of the uncompacted subsurface native soil
- Stone reservoir void capacity

Where additional runoff from adjacent impervious areas is not directed to the PPS, the necessary design thickness of the stone reservoir may simply be considered the depth of water collected from the design storm event divided by the void percentage of the stone reservoir. This design thickness will store all of the water from the storm event. This may be adequate for basic estimation purposes; however, the final design thickness determination shall be performed by a licensed engineer who is fluent in hydrologic design and calculation.

B. The choker course will serve as the stabilizing layer of base aggregate on which the surface porous asphalt pavement layer(s) will be placed. The choker course shall be of a compacted thickness not more than 1.5 inches.

4. Maintenance Considerations

A. Signs intended primarily for maintenance personnel should be posted at porous pavement locations to indicate the following:
   - Abrasives such as sand shall not be used for winter maintenance.
   - Pavement surface shall not be seal coated.
   - Deposits of mulch or soil and debris on the porous surface should be reported to the appropriate district/maintenance office.
   - Ponded water on the porous pavement surface should be reported to the appropriate district/maintenance office.

B. Vacuuming of the surface should take place annually, and whenever clogging or potential clogging is suspected.

C. Daylight drains that serve as overflow or auxiliary drainage should be inspected annually.

Specification References

S1. Hydrologic Soil Groups, Chapter 7. Part 630, Hydrology. National Engineering Handbook. Natural Resources Conservation Service. United States Department of Agriculture. 2007.
https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/NEHhydrology/ch7.pdf

S2. Porous Pavement. Stormwater Solutions, Water and Watershed Education. Oregon State University Extension Service.
http://extension.oregonstate.edu/stormwater/porous-pavement

Appendix B. Special Provision for Porous Pavement Structure - DRAFT

ITEM # 0406XXXA   POROUS PAVEMENT STRUCTURE (PPS)

Description: Work under this section shall include the design and construction of a porous pavement structure (PPS), to the grade and cross section shown on the plans, and shall conform to the relevant provisions of the Standard Specifications Form 817, including but not limited to the following: Section 2.02, Roadway Excavation, Formation of Embankment, and Disposal of Surplus Material, Section 2.05, Trench Excavation, Section 2.06, Ditch Excavation, Section 2.09, Subgrade, Section 4.06 Bituminous Concrete, Section 7.51, Underdrain and outlets, Section 7.55, Geotextile Filter Fabric, and Materials Sections M.01, M.02, M.04 and M.08, and supplemented as follows, or as directed by the Engineer.

List of terms and definitions:

The terms listed below as used in this specification are defined as:

Choker/stabilizing layer – a layer of fine aggregate used to reduce the infiltration or erosion of fine soils (silts and clays).

Geotextile membrane - permeable fabrics which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain.

Hydrologic conductivity - the ease with which a fluid (usually water) can move through pore spaces or fractures.

Hydrologic study - a study of the amount and quality of water being stored or conveyed on the land surface, and in soils and rocks near the surface.

Hydrologic Soil Groups - a group of soils having similar runoff potential under similar storm and cover conditions. The United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) defines four soil groups:

- Group A is sand, loamy sand or sandy loam types of soils having a high rate of water transmission. It has low runoff potential and high infiltration rates even when thoroughly wetted.
- Group B is silt loam or loam. It has a moderate infiltration rate when thoroughly wetted.
- Group C soils are sandy clay loam. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water.

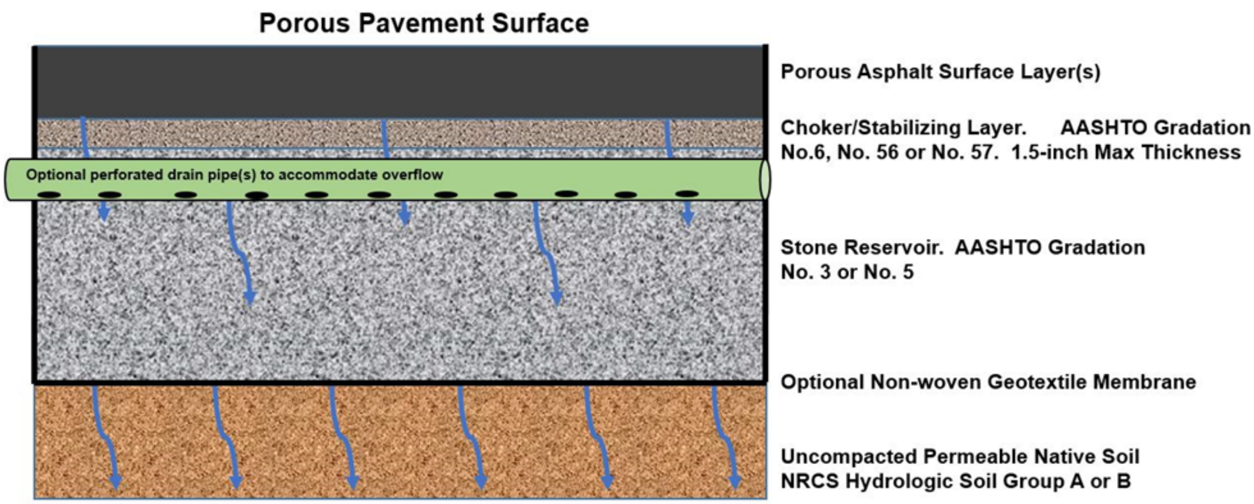
- Group D soils are clay loam, silty clay loam, sandy clay, silty clay or clay. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, and shallow soils over nearly impervious material.

Impervious pavement – a typical dense graded pavement with typically 3-8% air voids that is not conducive to water infiltration/penetration.

Porous pavement – an open graded pavement with greater than 18% air voids to promote drainage of water via gravity.

Stone reservoir – A designed subsurface coarse-aggregate layer where water can be temporarily stored until it gradually percolates into an underlying uncompacted permeable native soil.

Porous Pavement Cross Sectional Diagram



Materials: The materials furnished for this work shall conform to the requirements of Sections M.01- M.10 where applicable. The specific materials to be used for the PPS shall be as directed by the Engineer and shall meet the following requirements:

Aggregate Layers Materials Selection

A. To maximize storage capacity, the aggregate gradation for the stone reservoir shall meet the ranges specified for AASHTO No. 3 in Table 1 of AASHTO M43. This gradation is also found in Table M.01.01 of the CTDOT Form 817. If deemed acceptable by the engineer, a finer gradation may be allowed such as AASHTO No. 5. It is emphasized that AASHTO No. 3 will have a higher void content and associated water storage capacity than No. 5.

B. The gradation for the material in the choker/stabilizing layer shall meet the ranges specified for AASHTO No. 6, AASHTO No. 56 or AASHTO No. 57 in Table 1 of AASHTO M43.

C. In addition to the gradation requirements, the aggregates selected for use in both the stone reservoir and the choker/stabilizing layers shall meet the requirements in Table 1 below. All stone reservoir and choker/stabilizing layer coarse aggregates shall be of a uniform, clean, crushed condition.

Table 1. Stone Reservoir and Choker/Stabilizing Coarse Aggregate Requirements

Flat & Elongated (5:1 ratio)	≤ 10%
2 Fractured Faces	95 – 100%
L.A. Abrasion loss (500 Revolutions)	≤ 50%

Asphalt Binder Selection for Porous Asphalt Pavement Surface Layer(s)

A. The asphalt binder used for the porous asphalt layers, will meet the requirements for one of the following:

- PG 76-22 modified with SBS polymer
- PG 64E-22 modified with SBS polymer

B. The separation tendency of the polymer from the binder shall be verified in accordance with ASTM D7173 using the Dynamic Shear Rheometer (DSR). In accordance with AASHTO T315, the DSR $G^*/\sin(\delta)$ results from the top and bottom sections of the ASTM D7173 test shall not differ by more than 10%. The results of ASTM D7173 shall be included on the Certified Test Report.

C. The supplier of the polymer modified binder shall indicate the maximum temperature to which the binder may be heated without damaging the polymer. This information shall accompany the material certification.

D. When polymer modifiers are not used, the binder shall be reinforced with fibers of either polyester or nylon.

E. In all cases, regardless of asphalt binder material selection, the mixtures must be tested in accordance with and meet the requirements of the next section below for “Porous Asphalt Pavement Surface Layers”.

Aggregate Selection & Mix Requirements for Porous Asphalt Pavement Surface Layer(s)

A. The aggregates used in the porous asphalt layer(s) shall meet the requirements for CTDOT Superpave Level 2 mixes.

B. The Job Mix Formula shall conform to the following master range:

Sieve Size	Percent Passing
0.75"	100%
0.50”	80–100%
0.375”	55-75%
#4	10-25%
#8	5-10%
#200	3-5%

C. The mixture shall be compacted in accordance with AASHTO T312 or AASHTO T245.

D. Mixes compacted using a Superpave gyratory compactor shall be compacted with 50 gyrations. The maximum specific gravity of the mixture shall be measured in accordance with AASHTO T209 and air void determination made in accordance with AASHTO T269. The specimens shall have air voids at 50 gyrations of not less than 16%. AASHTO T331 shall be used to measure the bulk specific gravity of the compacted specimen.

E. Mixes compacted using Marshall Design procedures shall be compacted with 50 blows of the Marshall hammer. The maximum specific gravity of the mixture shall be measured in accordance with AASHTO T209 and air void determination made in accordance with AASHTO T269. The specimens shall have air voids at 50 blows of not less than 16%. AASHTO T331 shall be used to measure the bulk specific gravity of the compacted specimen.

F. The average asphalt binder film thickness shall be not less than 12.0 microns as calculated in accordance with CTDOT form MAT412s.

G. A dense graded mixture utilizing aggregates of the same parent source shall be tested in accordance with AASHTO T283. The minimum Tensile Strength Ratio of that set of specimens will be 80%. If the dense graded mixture does not achieve the minimum required Tensile Strength Ratio, then an anti-strip additive shall be blended with the asphalt binder used in the mixture for the PPS.

H. The mixture shall be tested in accordance with AASHTO T305 with a maximum allowable draindown of 0.3%. Fibers are permitted for use. If the draindown requirement cannot be met then the addition of polyester or nylon fibers to the mix will be required to reduce draindown values to acceptable limits so long as all other mix requirements are met.

I. The mixture shall be subjected to Cantabro testing in the Los Angeles machine in accordance with Tex-245-F [ref. S3]. The mixture shall be oven aged for 2 hours at compaction temperature in accordance with AASHTO R30 prior to compaction of the Cantabro specimens. The specimens shall show a Cantabro Loss of not more than 35.0% after 300 continuous revolutions. If these requirements cannot be met then further development of the mixture is required until the loss comes into conformance.

J. A workability additive is permitted to be used to aid in production and placement. Workability additives shall not negatively impact the performance criteria of the mixture.

Design of Aggregate Layers

B. The final design thickness shall, as a minimum, take into consideration all of the following elements.

- Typical design storm rainfall depth
- Total stormwater collection surface area (including surrounding areas where drainage is directed to the PPS)
- Total stone recharge bed surface area
- Infiltration rate of the uncompacted subsurface native soil
- Stone reservoir void capacity

Where additional runoff from adjacent impervious areas is not directed to the PPS, the necessary design thickness of the stone reservoir may simply be considered the depth of water collected from the design storm event divided by the void percentage of the stone reservoir. This design thickness will store all of the water from the storm event. This may be adequate for basic estimation purposes, however the final design thickness determination shall be performed by a licensed engineer who is fluent in hydrologic design and calculation.

B. The choker course will serve as the stabilizing layer of base aggregate on which the surface porous asphalt pavement layer(s) will be placed. The choker course shall be of a compacted thickness not more than 1.5 inches.

Production QA Requirements

A. At least one sample shall be collected from haul units for every 600 tons of produced material.

B. A minimum of one test shall be conducted per PPS.

C. Test portions shall be split to size in accordance with AASHTO R47

D. Maximum specific gravity shall be measured on the collected mix in accordance with AASHTO T209.

E. Specimens shall be compacted in a Superpave Gyratory Compactor in accordance with AASHTO T312 with 50 gyrations or in a Marshall compactor in accordance with AASHTO T245 with 50 blows of the Marshall hammer. Compaction of the test specimen will be in accordance with the method used in the mix design. Bulk specific gravity of the specimens shall then be determined on the compacted specimens in accordance with AASHTO T331.

F. Subsequent air void calculations shall be conducted in accordance with AASHTO T269.

G. Air voids as measured shall fall within the range of 16% to 22%.

H. Asphalt content of the plant produced mix shall be measured in accordance with AASHTO T308.

I. The asphalt content as measured shall be input into the CTDOT form MAT412s.

J. Mechanical analysis of the extracted aggregate from AASHTO T308 shall take place in accordance with AASHTO T30. The resulting gradation shall conform to the ranges stated in Section V.B. and input into the CTDOT form MAT412s

K. The average binder film thickness as calculated and reported on CTDOT form MAT412s shall be a minimum of 12.0 microns.

Construction Methods: Porous Pavement Structure(s) shall be installed by the Contractor in location(s) shown on the plans or as directed by the Engineer.

Excavation & Site Preparation

A. Adjacent surfaces and structures shall be stabilized prior to excavation to prevent soil and contaminant laden runoff from running onto the site. This may include the use of vegetation, barriers and/or silt fence and geotextiles to prevent runoff onto the site.

B. Excavation shall be conducted utilizing tracked equipment to distribute the load over a wider area and reduce the risk of compacting the subsurface native soil (infiltration bed), which if it occurs will negatively impact infiltration rates.

C. Required depth of excavation will be confirmed and approved by the engineer.

D. Upon approval of the final infiltration bed depth, placement of geotextile fabric (if used) shall take place immediately.

E. Following the approval of final infiltration bed depth, completion of the PPS shall take place expeditiously to reduce the risk of runoff running onto the excavated site.

F. If sub-drains or overflow measures are included in the structure they shall be assembled and placed immediately prior to the first lift of the stone reservoir.

Construction & Compaction of Aggregate Layers

A. The stone reservoir shall be placed in lifts of not more than 10 inches and, to ensure void capacity, compacted with no more than 1-2 passes of a lightweight roller or a vibratory plate compactor.

B. The choker course shall be placed at a compacted thickness of not more than 1.5 inches and compacted to the asphalt base grade with no more than 1-2 passes of a lightweight roller or a vibratory plate compactor.

C. Adequate placement of the aggregate layers in the porous structure shall be determined and approved by the engineer prior to placement of the porous asphalt base and/or surface layers.

Construction & Compaction of Porous Asphalt Pavement Surface Layers

A. Tack coat of any kind shall <u>not</u> be applied over the compacted aggregate layers or between the compacted porous asphalt layers. All other surfaces that will contact the porous asphalt such as utility structures, sidewalk edges, curbs and gutters shall be coated with Type RS-1 emulsion prior to placement of the asphalt layers.

B. Surface temperatures at the time of placement of any porous asphalt layers shall be a minimum of 50º F and rising.

C. Porous asphalt layers shall be placed in 2 lifts when a single lift cannot be adequately placed and compacted.

D. Each lift shall be spread with a suitable track paver such that the weight of the paver is distributed over as large a surface area as possible.

E. Breakdown rolling shall proceed immediately following placement. Two to four (2-4) passes of a static roller is suggested to accomplish this.

F. Finish rolling is recommended to occur between surface temperatures of 150 and 200º F. A 1-ton static roller is suggested for finish rolling.

G. Completion of finish rolling shall be determined when roller marks are smoothed sufficiently. This shall be decided by the engineer.

H. All constructed joints shall be butt/vertical joints. The cold side of any construction joint shall be coated with Type RS-1 emulsion. Every effort shall be made to close in joints on a daily basis.

Method of Measurement: Payment lines for earth excavation will coincide with the slope and subgrade lines or the top of the payment lines for ditch excavation, whichever applies, as shown on the plans or as ordered. All costs incidental to the disposal of unsuitable excavated material will be included in the price for "Earth Excavation." Any surplus or unsuitable material not required, nor permitted to be used onsite, shall be disposed of in accordance with Form 817, Subarticle 2.02.03‐10. Excavation of materials (earth, unsuitable material, trench or ditch, as applicable) will be measured upon removal. Quantities will be determined by the net weight, in tons, measured in the hauling vehicles furnished by and at the expense of the Contractor.

The stone reservoir will be measured in place after final grading and compaction. The total thickness shall be as indicated on the plans, or as ordered by the Engineer, within a tolerance of -3/4 in to +1/2 in. Measurements to determine the thickness will be taken by the Engineer at lateral intervals of 25 ft or less, (with a minimum of 10 measurements) and shall be considered representative of the layer.

The choker/stabilizing layer will be measured in place after final grading and compaction. The total thickness shall be as indicated on the plans, or as ordered by the Engineer, within a tolerance of -± 1/2 in.. Measurements to determine the thickness will be taken by the Engineer at lateral intervals of 25 ft or less, (with a minimum of 10 measurements) and shall be considered representative of the layer.

If a thickness measurement is taken and found deficient, additional measurements considered necessary by the Engineer will be taken to determine the limits of the deficiency. Areas not within allowable tolerances shall be corrected, as ordered by the Engineer, without additional compensation to the Contractor.

The quantities of porous asphalt pavement, aggregates for stone reservoir, and aggregates for the choker/stabilizing layer to be included for payment will be determined by the net weight, in tons, measured in the hauling vehicles furnished by and at the expense of the Contractor. The scales shall be of a type satisfactory to the Engineer and shall be sealed by the Department of Consumer Protection at the expense of the Contractor, as often as the Engineer may require. . An inspector, to be appointed and compensated by the Department, shall check the weight of all material entering into construction. The total weight will be the summation of the weigh slips of pavement or aggregates actually incorporated in the work included under this item.

Geotextile filter fabric (if used) will be measured for payment by the actual number of square yards of the type indicated on the plans or authorized by the Engineer. Geotextile specifically included in the payment of another item will not be measured for payment under this item.

Underdrains (if used) will be measured for payment by the actual number of linear feet of underdrains, and outlets for underdrains, completed, accepted and measured in place.

Basis of Payment: This work will be paid for at the contract unit price per ton for furnishing and placing porous asphalt pavement; per cubic yard for aggregates; and per cubic yard for earth excavation, complete in place and accepted by the Engineer, which price shall include furnishing all materials, equipment, tools, labor and work incidental thereto. Geotextiles will be paid for at the Contract unit price per square yard, complete in place, which price shall include all materials, labor, tools, and equipment incidental and necessary for each type of installation.

Payment for underdrains, and outlets for underdrains will be on the basis of unit price per linear foot, which price shall include pipe of the size specified, elbows, tees, wyes, couplings, fitting, trench excavation, geotextile, aggregate, sand, tools, material and labor incidental thereto. Material for tack coat will be measured in gallons.

Pay Items	Pay Unit
Excavation	c.y.
Geotextile Filter Fabric	s.y
Aggregate for Stone reservoir	c.y.
Aggregates for Choker/stabilizer layer	c.y.
Porous Asphalt Pavement	ton (t)
Material for Tack Coat	gal
Underdrains	l.f
Outlet for underdrains	l.f.
Slotted drain pipe	l.f.

References

S3. Test Procedure for Cantabro Loss. Designation Tex-245-F. Texas Department of Transportation. Construction Division. September2014.