December 2007
Technical Memorandum: UCPRC-TM-2008-07

State of the Practice in 2006 for Open-Graded Asphalt Mix Design

Author:
A. Ongel, J.Harvey, and E. Kohler

Partnered Pavement Research Center Strategic Plan Element No. 4.16: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types

PREPARED FOR:

California Department of Transportation
Division of Research and Innovation
Office of Roadway Research

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

DOCUMENT RETRIEVAL PAGE	**Technical Memorandum:** UCPRC-TM-2008-07

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Prepared for:	**FHWA No.:**	**Date Work Submitted:**	**Date:**
Caltrans Division of Research and Innovation	CA111200B	May 19, 2008	December 2007

Strategic Plan No:	**Status:**	**Version No:**
4.16	Stage 6 final	1

Abstract:
This document presents a survey performed in 2006 of the materials and procedures used to produce asphalt mixes with an open aggregate structure in the United States and in Europe. In the U.S. these types of materials are known as "open-graded mixes" and they are utilized mostly to improve permeability and, consequently, wet-weather friction, which is related to the frequency of traffic accidents. In Europe, these materials are known as "porous asphalt mixes" and they are used for the same reasons as in the U.S., as well as to lessen tire/pavement noise.

In general, European porous mixes have higher air-void contents than those in the U.S., ranging between 20 and 25 percent; open-graded mixes in the U.S. generally have air-void contents of less than 20 percent. European countries have specifications for horizontal and vertical permeabilities, while there are no permeability specifications in the U.S. However in both Europe and the U.S., a maximum particle loss of 50 percent from the LA abrasion test is specified. In Europe, the tensile strength ratio for porous mixes is specified as at least 50 percent; in the U.S. however, only a few states specify a tensile strength ratio. The required value is usually above 80 percent for those states that have a tensile strength ratio specification.

Keywords:
Porous asphalt, open graded mix, asphalt mix design, aggregate gradation

Related documents:
University of California Pavement Research Center. (June 2005). *Work Plan for "Investigation of Noise, Durability, Permeability and Friction Performance Trends for Asphaltic Pavement Surface Types."* Partnered Pavement Research Center, Strategic Plan Item 4.16. (UCPRC-WP-2005-01)

Signatures:

A. Ongel **1st Author**	J. Harvey **Technical Review**	D. Spinner **Editor**	J. Harvey **Principal Investigator**	T. J. Holland **Caltrans Contract Manager**

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

The research presented in this report is part of the Caltrans Quieter Pavement Research (QPR) Work Plan. The central purpose of the research is to support the Caltrans Quieter Pavement Research Program, which has as its goals and objectives the identification of quieter, safer, smoother, and more durable asphalt pavement surfaces. The program Road Map and Work Plan outline the tasks carried out in this research.

The research conforms with FHWA guidance provided to state departments of transportation that conduct tire/pavement noise research.

This work includes the following objectives:

1. Provide a literature survey of U.S. and European practice and research regarding the performance of asphaltic surfaces.
2. Develop an operational capacity at the Partnered Pavement Research Center to measure field on-board sound intensity, laboratory noise impedance, and field surface friction.
3. Develop a database structure for field and laboratory measurements collected in this project.
4. Measure the properties of as-built surfaces (sound intensity, permeability, friction, and distresses) over time, with trends in data summarized annually; continue data collection as authorized by Caltrans; measure the same properties on mixes from outside California; and summarize data and trends reported from outside California.
5. Perform statistical analysis on measurement results from field and laboratory, and report performance trends and modeling results.
6. Prepare a report summarizing the work of the first five objectives.

This technical memorandum satisfies Objective 1 listed above.

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LIST OF ABBREVIATIONS USED IN THE TEXT

AASHTO	American Association of State Highway and Transportation Officials
AAV	Aggregate abrasion value
AC	Asphalt cement
ADT	Average daily traffic
AR	Asphalt rubber
AR-ACFC	Asphalt rubber asphalt concrete friction course
ARB	Asphalt rubber binder
BMTP	Bituminous Mixture Test Protocol
CRM	Crumb rubber modifier
DOT	Department of Transportation
FC	Friction course
FHWA	Federal Highway Administration
ITSR	Indirect tensile strength ratio
LA abrasion test	Los Angeles abrasion test
MOGFC	Modified asphalt binder open-graded friction course
NCAT	National Center for Asphalt Technology
NMAS	Nominal maximum aggregate size
OGAC	Open-graded asphalt concrete
OGFC	Open-graded friction course
PA	Porous asphalt
PCC	Portland cement concrete
PEM	Porous European mix
PG	Performance grade
PMAC	Polymer-modified asphalt cement
PSV	Polished stone value
RAC-O	Open-graded rubberized asphalt concrete
RAC-O-HB	High-bitumen open-graded rubberized asphalt concrete
SB	Styrene butadiene
SBS	Styrene butadiene styrene
TSR	Tensile strength ratio
VFA	Voids filled with asphalt

1 INTRODUCTION

The research presented in this report is part of the Caltrans Quieter Pavement Research (QPR) Work Plan. The central purpose of the research is to support the Caltrans Quieter Pavement Research Program, which has as its goals and objectives the identification of quieter, safer, smoother, and more durable asphalt pavement surfaces. The QPR Road Map and Work Plan outline the tasks carried out in this research. The research conforms with FHWA guidance provided to state departments of transportation that conduct tire/pavement noise research.

For the flexible pavement part of the QPR study, Caltrans identified a need for research in the areas of acoustics, friction, and pavement performance of asphalt pavement surfaces for the state highway network. In November 2004, the Caltrans Pavement Standards Team (PST) approved a new research goal for the Partnered Pavement Research Center (PPRC) Strategic Plan; it was numbered Element 4.16 and titled "Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types."

This work includes the following objectives:

1. Provide a literature survey of U.S. and European practice and research regarding the performance of asphaltic surfaces.
2. Develop an operational capacity at the Partnered Pavement Research Center to measure field on-board sound intensity, laboratory noise impedance, and field surface friction.
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5. Perform statistical analysis on measurement results from field and laboratory, and report performance trends and modeling results.
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A literature survey reviewing the performance of asphalt surfaces for noise, permeability, friction, smoothness, and durability was included in a chapter of another report that is a deliverable of this project, titled "Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-year Results." This technical memorandum presents an additional literature survey of open-graded asphalt specifications and mix design in the U.S. and Europe. Together, these documents complete the first objective of PPRC SPE 4.16.

Chapter 2 of this technical memorandum presents a review of practices in the U.S. Chapter 3 presents a review of practices in Europe. In both chapters the survey is of practices as of 2006. Chapter 4 presents a summary of the major findings of the literature survey.

2 MIX DESIGNS IN THE UNITED STATES

Open-graded mixes have been used in the United States for more than 50 years. They have higher voids content than conventional asphalt mixes, which are around 15 to 25 percent. Open-graded mixes have been used by most states; however, the performance experienced by each state has been different. According to a 1998 survey, 38 percent of the states discontinued using open-graded asphalt due to unacceptable performance, while 38 percent have experienced good performance and were still using open-graded asphalt mixes (1). The different performance of open-graded mixes is due to the different mix designs used in each state as well as to the different environmental and traffic conditions. Open-graded mixes usually are used as thin overlays in the United States, and they are called open-graded friction courses. This section summarizes the open-graded mix designs and their performance in the United States across a wide range of sources.

2.1 Federal Highway Administration (FHWA)

In 1990, the FHWA published the technical advisory T 5040.31 for open-graded friction courses (2). According to the FHWA mix design, polish-resistant, high-quality aggregates should be used to provide good frictional characteristics. At least 75 percent of the coarse aggregates should have two fractured faces, and 90 percent of the coarse aggregates should have one or more fractured faces. Abrasion loss as measured by the AASHTO T 96 test method should not be more than 40 percent. The recommended grade of asphalt cement is AC-20. Mineral filler should meet the specifications of AASHTO M 17. Additives may be required to improve the properties of the asphalt binder to resist stripping, retard aging, or improve temperature susceptibility. The recommended mix design gradation is given in Table 1.

Table 1: FHWA Mix Design Gradation Specification

Sieve Size	Percent Passing (by weight)
12.50 mm (1/2 in.)	100
9.50 mm (3/8 in.)	95 to 100
4.75 mm (No.4)	30 to 50
2.36 mm (No. 8)	5 to 15
75 µm (No. 200)	2to 5

The design steps in the FHWA method are as follows:

- Compute specific gravity.
- Test the asphalt cement viscosity for compliance with AASHTO M 226.
- Determine percentage of oil retained on the aggregate by soaking in S.A.E. No.10 lubrication oil and draining.
- Estimate asphalt content based on the percentage of oil retained on the aggregate (AASHTO T 270).
- Determine void content in coarse aggregate by compacting it with a vibration hammer in a mold.
- Calculate the amount of fine aggregate that needs to be added.

- Apply tests for draindown of mastic, binder, and fine aggregate at different temperatures to determine the mixing temperature.
- Apply the immersion-compression test to determine resistance to effects of water.

2.2 California

As of early in 2006, California used AR-4000, AR-8000, polymer-modified asphalt (PBA), and rubberized asphalt concrete as open-graded asphalt concrete (OGAC) binders (3, 4). The California Department of Transportation (Caltrans) specifies two types of asphalt rubber mixes: open-graded rubberized asphalt concrete (RAC-O) and high-bitumen content RAC-O (RAC-O-HB). RAC-O-HB has higher bitumen content (around 8 to 10 percent by mass of dry aggregate) than RAC-O.

Since this literature survey was completed in early in 2006, Caltrans has changed to the use of PG binder classifications, and recently updated Section 39 of the Standard Specifications, covering asphalt materials. A Caltrans *Design Information Bulletin* (DIB 86, [5]) published on November 30, 2006, provides guidance for use of PG binders for open-graded mixes. It requires the following binders based on California climate region and placement temperature:

- South Coast, Central Coast, Inland Valleys: PG 64-10 for placement temperature greater than 21°C (70°F); PG 58-34 PM (polymer modified) otherwise
- North Coast: PG 64-16; PG 58-34 PM otherwise
- Low Mountain, South Mountain: PG 64-16; PG 58-34 PM otherwise
- High Mountain, High Desert: PG 64-28; PG 58-34 PM otherwise
- Desert: PG 70-10; PG 58-34 PM or PG 64-28 PM otherwise (PG 64-28 may be specifically requested)

Caltrans specifies two gradations for open-graded mixes: one with a 12.5-mm nominal maximum aggregate size (NMAS), and the other with a 9.5-mm NMAS. Aggregates should be hard and abrasion resistant.

California OGAC mix design is based on a draindown test. A draindown test (CT 368) is specified to determine the optimum binder content that can be used without excessive draindown during transportation and placement of the mix. For modified open-graded mixes, draindown is set only for AR-4000, and this value is used for mix design. The conventional AR-4000 binder content is multiplied by 1.2 to determine the binder content of RAC-O mixes, and it is multiplied by 1.65 to determine the binder content of RAC-O-HB mixes. A moisture sensitivity test is not required. Mix design requirements are shown in Table 4 and Table 7 at the end of this chapter.

2.3 Arizona

The Arizona DOT started using open-graded mixes in the 1950s to provide surface skid resistance and good ride quality (6). The gradation of its open-graded mixes changed over the years, with emphasis on the use of a single-size aggregate. Arizona uses asphalt rubber binder [asphalt rubber asphalt concrete friction course (AR-ACFC)] for its open-graded mixes. Asphalt rubber binder consists of 80 percent hot paving-grade asphalt and 20 percent ground tire rubber. Asphalt binder content ranges between 9 and 10 percent by weight of the mix. An NMAS of 9.5 mm and a minimum air-void content of 15 percent are specified for AR-ACFC.

The rubber asphalt grade can be performance grade (PG) 64-16, PG 58-22, or PG 52-28. Coarse aggregates should be crushed gravel, crushed rock, other inert material, or a combination of these. A minimum of 85 percent of the coarse aggregates should have two fractured faces. Fine aggregates should consist of natural sand, sand prepared from rock, or other inert material. AR-ACFC uses 1 percent mineral admixture by weight to help prevent stripping. Mineral admixture can be either Type II portland cement or hydrated lime. AR-ACFC is placed 12.5 mm thick when used on flexible pavement, and it is placed 25 mm thick on PCC pavements. Mix design requirements are given in Table 4 at the end of this chapter.

2.4 Florida

Florida has been using open-graded mixes since 1970 to improve skid resistance in wet weather. On high-speed (above 80 km/h), multi-lane roads, open-graded friction courses are specified to allow the water to be drained away from the tire pavement contact area. Two types of open-graded mixes, friction course 2 (FC-2; older mix) and FC-5 (newer mix), are used in Florida (7). FC-2 mix has an NMAS of 9.5 mm, and FC-5 has an NMAS of 12.5 mm.

Crushed granite, gravel, slag, or oolitic limestone can be used as coarse aggregate in FC-2 mix. Ninety percent of FC-2 mix designs use crushed oolitic limestone aggregate due to its non-polish characteristics. According to the Florida DOT specifications, 85 percent of crushed gravel should have three crushed faces.

FC-5 mix requires aggregates to be 100 percent polish resistant crushed granite or crushed oolitic limestone. Hydrated lime, 1 percent by weight of the total dry aggregate, is added to the mix if granite is used. Fiber stabilizer additives, mineral or cellulose fibers, are needed for FC-5 mix. Mineral fibers are added at a dosage rate of 0.4 percent by total mix weight, and cellulose fibers are added at a dosage rate of 0.3 percent by total mix weight. FC-5 mix is usually placed 20 mm (3/4 inch) thick. Mix design requirements of Florida open-graded mixes are shown in Table 4 and Table 6 at the end of this chapter.

Florida uses asphalt rubber binder 12 (ARB-12), which meets the requirements of PG 67-22 binder, blended with 12 percent ground tire, for both FC-2 and FC-5 mixes. The newer FC-5 mix is thicker than FC-2 mix and contains fibers. Hence, it is expected to perform better. Asphalt binder contents for FC-2 and FC-5 mixes are given in Table 2 and Table 3, respectively.

Table 2: Asphalt Binder Content for Florida Friction Course Mixes FC-2

Aggregate Type	Binder Content (by weight of total mix)
Crushed granite	5.5 to 7.0%
Crushed slag	6.0 to 8.0%
Crushed limestone (oolitic)	6.5 to 7.5%
Lightweight	12.5 to 15.0%

Table 3: Asphalt Binder Content for Florida Friction Course Mixes FC-5

Aggregate Type	Binder Content (by weight of total mix)
Crushed granite	5.5 to 7.0%
Crushed limestone (oolitic)	6.5 to 8.0%

2.5 Oregon

Oregon has been using open-graded asphalt concrete (F-mix) since the 1970s. It is used widely, including on interstate highways (8). Oregon DOT (ODOT) specifies two gradations for open-graded mixes: one with an NMAS of 12.5 mm and the other with an NMAS of 19 mm. Binder can be unmodified asphalt, PBA-5; or modified asphalt, PBA-6.

The Oregon DOT specifies a draindown test; a maximum draindown of 30 percent is allowed if the National Center for Asphalt Technology (NCAT) draindown test is used, and a maximum draindown of 70 to 80 percent is allowed if the ODOT draindown test is used. Lime treatment is required for aggregates on all heavy-duty projects. Hydrated lime content of 0.7 percent by weight of dry aggregates is specified. A minimum tensile strength ratio (TSR) of 80 percent is also required for open-graded mixes. Mix design requirements are given in Table 6 at the end of this chapter.

The surface lift thickness is based on the nominal maximum aggregate size. The minimum thickness should be more than or equal to 1.2 to 2 times the maximum aggregate size. Oregon DOT recommends a minimum 2 in. (50 mm) thickness for the 19-mm NMAS open-graded mixes and 1.5 in. (40 mm) thickness for the 12.5-mm NMAS open-graded mixes.

2.6 Georgia

The Georgia DOT specifies three types of open-graded mixes (9, 10). The Georgia DOT first specified a mix with an NMAS of 9.5 mm and designed according to the FHWA open-graded mix design procedure. However, performance of this mix was poor, so the Georgia DOT developed an open-graded mix with an NMAS of 12.5 mm and composed of aggregates, polymer-modified asphalt cement (PMAC), and stabilizing fibers; the mix also includes hydrated lime as an anti-stripping agent. More recently, the Georgia DOT adapted a porous European mix (PEM) with a 12.5-mm NMAS as the third open-graded mix. PEM has a coarser gradation that makes it more permeable than the earlier mixes. PEM also contains aggregates, a polymer modifier, stabilizing fibers, and hydrated lime.

The Georgia DOT uses two types of polymer, styrene butadiene (SB) and styrene butadiene styrene (SBS) for its open-graded mixes. Polymer modifier is added at a rate of 4.0 to 4.5 percent by weight of the asphalt cement. Fiber addition is also specified for 12.5-mm mixes to reduce draindown. Mineral fibers are added at a dosage rate of 0.4 percent by weight of the mix, and cellulose fibers are added at a dosage rate of 0.3 percent by weight of the mix.

Polish-resistant, crushed aggregates are used in the mix design. Air-void content of 18 to 20 percent is specified for open-graded mixes, and air-void content of 20 to 24 percent is specified for PEM mixes. The NCAT draindown test is required. Mix design requirements of Georgia open-graded mixes are given in Table 4 and Table 6 at the end of this section.

2.7 Texas

The Texas DOT specifies two mix designs for open-graded mixes (11): one with PG binder and the other with asphalt rubber binder ("A-R mixture"). Both have an NMAS of 9.5 mm. For asphalt mixes with PG binders, mineral or cellulose fibers and 1 to 2 percent lime mineral filler by weight of the mix are specified. Anti-stripping can also be used depending on the project. A higher-temperature-grade binder such as PG-76 is used as the PG binder.

Binder content for the PG-76 mixture ranges from 5.5 to 7 percent, and binder content for rubber asphalt binder ranges from 8 to 10 percent. Mix design is based on the target aggregate gradation and binder content. Unlike other states, Texas conducts a Cantabro test on the mixes, and the maximum Cantabro loss is specified as 10 percent by weight of the total mix. Mix design requirements for Texas open-graded mixes are given in Table 7 at the end of this section.

2.8 New Jersey

New Jersey uses open-graded mixes to reduce traffic noise and increase wet-weather safety and ride quality. New Jersey specifies three gradations for open-graded mixes (12): one for 9.5-mm NMAS mixes and two for 12.5-mm NMAS mixes. Open-graded asphalt mixes can be unmodified open-graded friction course (OGFC) or modified OGFC (MOGFC). PG 64-22 asphalt binder is specified for unmodified mixes, and PG 76-22 is specified for modified mixes. Modified open-graded mixes contain polymer-modified binder with mineral or cellulose fibers. For mineral fibers the dosage rate is specified as 0.4 percent, and for cellulose fibers the dosage rate is specified as 0.3 percent by weight of the total mix.

The New Jersey DOT specifies the minimum asphalt content and air-void content depending on gradation and modification, as given in Table 4, Table 5, and Table 8 at the end of this chapter. Gneiss, granite, quartzite, or trap rock can be used as aggregates for open-graded mixes. The optimal asphalt content of conventional open-graded mixes is determined based on visual draindown analysis, while the optimal asphalt content of modified open-graded mixes is determined based on aggregate surface area, relative air voids in mineral aggregate, and visual draindown analysis.

The New Jersey DOT specifies a minimum TSR of 80 percent for open-graded mixes. New Jersey does not specify anti-stripping agents; however, if the minimum TSR requirement is not met, an anti-stripping agent may be used. New Jersey also specifies a minimum lift thickness for the open-graded mixes: 0.75 in. (19 mm) for the 9.5-mm NMAS mix, 1 in. (25 mm) for the modified 12.5-mm NMAS mix, and 1.25 in. (32 mm) for the unmodified 12.5-mm NMAS mix.

2.9 Alabama

Alabama uses polymer-modified PG 76-22 binder for its open-graded mixes. Alabama specifies two gradations (13): one with an NMAS of 9.5 mm and the other with an NMAS of 12.5 mm. Aggregate used in the open-graded mix should be 100 percent crushed, virgin aggregates such as granite, blast-furnace slag, sandstone, or manufactured lightweight aggregate. Mineral filler or agricultural limestone may be used when additional dust (material passing a No. 200 sieve) is needed.

Asphalt binder content is specified as 5.6 to 9.0 percent (by weight of the mix) for the 9.5-mm NMAS mix and 4.7 to 9.0 percent for the 12.5-mm NMAS mix. Open-graded mixes should be designed with a minimum air-void content of 12 percent. A fiber stabilizer is also needed for Alabama polymer-modified open-graded mixes. A minimum dosage rate of 0.3 percent by weight of the total mix is required for both cellulose and mineral fibers. The Alabama DOT also specifies a minimum TSR and draindown test (Test ALDOT-386) for open-graded mixes. The amount of draindown in an asphalt-aggregate sample should not exceed 0.3 percent. Minimum TSR should be 80 percent for open-graded mixes. Mix design requirements are given in Table 5 and Table 8 at the end of this section.

2.10 Nevada

The Nevada DOT specifies two gradations for open-graded mixes: one with an NMAS of 9.5 mm and the other with an NMAS of 12.5 mm (14, 15). A minimum of 90 percent of aggregates should have at least two crushed faces. The Nevada DOT also specifies the Los Angeles (LA) abrasion test and stripping test (Nev. T209) for aggregates of open-graded mixes. A hydrated lime conforming to American Society for Testing and Materials (ASTM) standard C1097 is specified as mineral filler. Asphalt can be AC 2.5, AC-5, AC-10, AC-20, AC-20P, AC-30, or AC-40. Mix design requirements are given in Table 5 and Table 8 at the end of this chapter.

2.11 Illinois

Illinois uses open-graded mixes with an NMAS of 9.5 mm (16). Aggregates can be crushed steel slag, crushed slug, crushed trap rock, or crushed stone. All the aggregates except crushed slag should satisfy the requirement for the LA abrasion test given in Table 5 at the end of this chapter.

Asphalt cement content of the open-graded mix should be between 5 to 15 percent of the weight of the mix. Asphalt cement grade should be either PG 58-22 or PG 64-22. An anti-stripping additive 0.5 percent to 1 percent by weight of the asphalt cement is also required. Mix design requirements are given in Table 5.

2.12 Kentucky

Kentucky uses open-graded mixes to provide a coarse-textured, well-draining, skid-resistant wearing surface. These mixes are usually placed 0.75-in. (19-mm) thick. Kentucky uses open-graded mixes with an NMAS of 9.5 mm (17, 18). Crushed gravel, crushed slag, crushed quartzite, crushed siltstone, crushed granite, dolomite, and limestone can be used as aggregates. Aggregates should be polish resistant. At least 95 of the coarse aggregates used in open-graded mixes should have one or more crushed faces, and 75 percent should have two or more crushed faces. Kentucky specifies performance-graded asphalt binder for its open-graded mixes. Asphalt binder can be PG 64-22, PG 70-22, or PG 76-22. An anti-stripping agent of 0.5 percent by weight of the asphalt binder is also specified. Mix design requirements are given in Table 5 at the end of this chapter.

2.13 Indiana

Indiana specifies two aggregate gradations for its open-graded mixes: one with an NMAS of 19 mm and the other one with an NMAS of 25 mm (19). The air-void content of open-graded mixes is specified as 15 to 20 percent. Binder content should be at least 3 percent by weight of the mix.

The Indiana DOT specifies PG binder for open-graded mixes. Fibers can also be incorporated into the mixture. A draindown test (AASHTO T 305) is required for open-graded mixes. Draindown of open-graded mixes should not exceed 30 percent. Mix design requirements of Indiana open-graded mixes are given in Table 9 at the end of this chapter.

Table 4: Characteristics of Open-Graded Mixes Used in the United States with 9.5-mm NMAS, Part 1 (California OGAC, Arizona AR OGAC, Florida OGAC FC-2, Georgia OGAC, and New Jersey OGAC)

	California OGAC (9.5-mm NMAS)	Arizona Asphalt Rubber OGAC (9.5 mm NMAS)	Florida OGAC (FC-2) (9.5 mm NMAS)	Georgia OGAC (9.5 mm NMAS)	New Jersey OGAC (9.5 mm NMAS)
Gradation (mm)					
12.50 mm (1/2 in.)	100	100	100	100	100
9.50 mm (3/8 in.)	90 to 100	100	85 to 100	85 to 100	85 to 100
4.75 mm (No.4)	29 to 36	30 to 45	10 to 40	20 to 40	20 to 40
2.36 mm (No. 8)	7 to 18	4 to 8	4 to 12	5 to 10	5 to 10
2.00 mm (No. 10)	-	-	-	-	-
1.18 mm (No. 16)	0 to 10	-	-	-	-
425 µm (No. 40)	-	-	-	-	-
75 µm (No. 200)	0 to 3	0 to 2.5	2 to 5	2 to 4	2 to 4
Asphalt Binder					
Grade	AR-4000, AR-8000, PBA-6a, PBA-6b previously; PG 64-10, PG 58-34 PM (polymer modified), PG 64-16, PG 64-28, PG 70-10, PG 64-28 PM since 2007	PG 64-16, PG 58-22, PG 52-28	PG 67-22	PG 76-22	PG 64-22
Content	-	-	5.5 to 15%	6.0 to 7.25%	5.5% minimum
Fiber Content	-	-	-	-	0.4% for mineral fibers; 0.3% for cellulose fibers
Aggregate Properties					
Water absorption	-	0 to 2.5%	-	-	1.7% maximum
Sand equivalent	-	55% minimum	-	70% minimum	-
Crushed faces	90% minimum	85% minimum 2 faces for coarse aggregates	85% minimum 3 crushed faces	85% minimum 1 or more crushed faces for coarse aggregates	-
Flakiness index	-	25% maximum	-	-	-
LA abrasion test 100 revolutions	10% maximum	9% maximum	-	15% maximum	-

	California OGAC (9.5-mm NMAS)	Arizona Asphalt Rubber OGAC (9.5 mm NMAS)	Florida OGAC (FC-2) (9.5 mm NMAS)	Georgia OGAC (9.5 mm NMAS)	New Jersey OGAC (9.5 mm NMAS)
LA abrasion test 500 revolutions	40% maximum	40% maximum	45% maximum; 50% if aggregate is granite	50% maximum	40% maximum
Carbonates	-	30% maximum	88% maximum	-	30% maximum
Soundness (Na_2SO_4)	-	-	12% maximum	-	10% maximum
Specific gravity	-	2.35 to 2.85	-	-	-
Flat and elongated particles	-	-	5:1 ratio; 10% maximum	5:1 ratio; 10% maximum	4:1 ratio; 7% maximum
Volumetric Properties					
Compaction method		-	-	Gyratory compactor	-
Air voids	-	-	-	18 to 20%	15%
Draindown	4.0 g from 4 kg aggregate sample	-	-	30% maximum	-
Voids filled with asphalt (VFA)	-	-	-	-	-

Table 5: Characteristics of Open-Graded Mixes Used in the United States with 9.5-mm NMAS, Part 2 (New Jersey MOGAC, Alabama PMOGAC, Nevada OGAC, Illinois OGAC, and Kentucky OGAC)

	New Jersey MOGAC (9.5-mm NMAS)	Alabama PMOGAC (9.5-mm NMAS)	Nevada OGAC (9.5-mm NMAS)	Illinois OGAC (9.5-mm NMAS)	Kentucky OGAC (9.5-mm NMAS)
Gradation (mm)					
12.50 mm (1/2 in.)	100	100	100	100	100
9.50 mm (3/8 in.)	85 to 100	90 to 100	95 to 100	90 to 100	90 to 100
4.75 mm (No.4)	20 to 40	30 to 50	40 to 65	30 to 50	25 to 50
2.36 mm (No. 8)	5 to 10	5 to 17	-	10 to 18	5 to 15
2.00 mm (No. 10)	-	-	-	-	-
1.18 mm (No. 16)	-	-	-	-	-
425 µm (No. 40)	-	-	12 to 22	-	-
75 µm (No. 200)	2 to 4	3 to 6	0 to 5	2 to 5	2 to 5
Asphalt Binder					
Grade	PG 76-22	Polymer-modified PG 76-22	AC 2.5, AC-5, AC-10, AC-20, AC-20P, AC-30, AC-40	PG 58-22, PG 64-22	PG 64-22, PG 70-22, PG 76-22
Content	6.0% minimum	5.6 to 9%	-	5 to 15%	-
Fiber Content	0.4% for mineral fibers 0.3% for cellulose fibers	0.3% minimum	-	-	-
Aggregate Properties					
Water absorption	1.7% maximum	-	4% maximum	-	3% maximum
Sand equivalent	-	-	-	-	-
Crushed faces	-	-	90% minimum 2 faces	-	95% minimum at least 1 face; 75% minimum 2 or more faces
Flakiness index	-	-	-	-	10% maximum
LA abrasion test 100 revolutions	40% maximum	-	-	-	-
LA abrasion test 500 revolutions	30% maximum	48% maximum (55% maximum for blast-furnace slag and sandstone)	37% maximum	40% maximum	40% maximum; 60% maximum for slag
Carbonates	-	-	-	-	
Soundness	10% maximum (Na_2SO_4)	10% maximum (Na_2SO_4)	12% maximum (Na_2SO_4)	12% maximum (Na_2SO_4)	9% maximum for limestone and dolomite; 12% for other aggregate types (Na_2SO_4)
Specific gravity	-	-	2.85 maximum	-	-
Flat and elongated particles	4:1 ratio; 7% maximum	5:1 ratio; 10% maximum 3:1 ratio; 20% maximum -	-	-	-
Volumetric Properties					
Compaction method	-	-	-	-	-
Air voids	18%	12% minimum	-	-	-
Draindown	-	0.3% by BMTP-386	-	-	-
VFA	-	-	-	-	-

Table 6: Characteristics of Open-Graded Mixes Used in the United States with 12.5-mm and 19-mm NMAS

	Oregon OGAC (19-mm NMAS)	Oregon OGAC (12.5-mm NMAS)	Georgia OGAC (12.5-mm NMAS)	Georgia European Mix (PEM) (12.5-mm NMAS)	Florida OGAC (FC-5) (12.5-mm NMAS)
Gradation (mm)					
25.00 mm (1 in.)	99 to 100	-	-	-	-
19.00 mm (3/4 in.)	85 to 96	99 to 100	100	100	100
12.50 mm (1/2 in.)	55 to 71	90 to 98	85 to 100	80 to 100	85 to 100
9.50 mm (3/8 in.)	-	-	55 to 75	35 to 60	55 to 75
4.75 mm (No.4)	10 to 24	18 to 32	15 to 25	10 to 25	15 to 25
2.36 mm (No. 8)	6 to 16	3 to 15	5 to 10	5 to 10	5 to 10
2.00 mm (No. 10)	-	-	-	-	-
1.18 mm (No. 16)	-	-	-	-	-
425 µm (No. 40)	-	-	-	-	-
75 µm (No. 200)	1 to 6	1 to 5	2 to 4	1 to 4	2 to 4
Asphalt Binder					
Grade	PBA-5, PBA-6	PBA-5, PBA-6	PG 76-22	PG 76-22	PG 67-22
Content	-	-	5.75 to 7.25%	5.5 to 7.0%	5.5 to 8%
Fiber Content	-	-	0.4% mineral fiber or 0.3% cellulose fiber	0.4% mineral fiber or 0.3% cellulose fiber	0.4% mineral fiber or 0.3% cellulose fiber
Aggregate Properties					
Water absorption	-	-	-	-	
Sand equivalent	45% minimum for fine aggregates	45% minimum for fine aggregates	70% minimum	70% minimum	-
Crushed faces	90% 2 faces for coarse aggregates; 75% 1 face for fine aggregates	90% 2 faces for coarse aggregates; 75% 1 face for fine aggregates	85% minimum 1 or more crushed faces for coarse aggregates	85% minimum 1 or more crushed faces for coarse aggregates	100% minimum
Flat and elongated particles	5:1 ratio; 10%maximum	5:1 ratio; 10% maximum	5:1 ratio; 10% maximum	5:1 ratio; 10% maximum	5:1 ratio; 10% maximum
LA abrasion test 100 revolutions	-	-	-	-	-
LA abrasion test 500 revolutions	30% maximum	30% maximum	50% maximum	50% maximum	45% maximum; 50% if aggregate is granite
Carbonates	-	-	-	-	88% maximum
Soundness	12% maximum (Na_2SO_4)	12% maximum (Na_2SO_4)	15% maximum ($MgSO_4$)	15% maximum ($MgSO_4$)	12% maximum (Na_2SO_4)
Specific gravity	-	-	-	-	-
Volumetric Properties					
Compaction method	Static	Static	Gyratory compactor	Gyratory compactor	-
Air voids	13.5 to 16%	13.5 to 16%	18 to 20%	20 to 24%	-
Draindown	30% maximum	30% maximum	30% maximum	30% maximum	-
VFA	40 to 50%	40 to 50%	-	-	-

Table 7: Characteristics of Open-Graded Mixes in the United States with 12.5-mm NMAS, Part 1 (California OGAC, California RAC-O, California RAC-O-HB, Texas OGAC, and Texas A-R OG)

	California OGAC (12.5-mm NMAS)	California RAC-O (12.5-mm NMAS)	California RAC-O-HB (12.5-mm NMAS)	Texas OGAC (12.5-mm NMAS)	Texas A-R OG (12.5-mm NMAS)
Gradation (mm)					
25.00 mm (1 in.)	-	-	-	-	-
19.00 mm (3/4 in.)	100	100	100	100	100
12.50 mm (1/2 in.)	95 to 100	95 to 100	95 to 100	80 to 100	95 to 100
9.50 mm (3/8 in.)	78 to 89	78 to 89	78 to 89	35 to 60	50 to 80
4.75 mm (No.4)	28 to 37	28 to 37	28 to 37	1 to 20	0 to 8
2.36 mm (No. 8)	7 to 18	7 to 18	7 to 18	1 to 10	0 to 4
2.00 mm (No. 10)	-	-	-	-	-
1.18 mm (No. 16)	0 to 10	0 to 10	0 to 10	-	-
425 µm (No. 40)	-	-	-	-	-
75 µm (No. 200)	0 to 3	0 to 3	0 to 3	1 to 4	0 to 4
Asphalt Binder					
Grade	AR-4000, AR-8000, PBA-6a, PBA-6b previously; PG 64-10, PG 58-34 PM (polymer modified), PG 64-16, PG 64-28, PG 70-10, PG 64-28 PM since 2007	AR-4000 plus 18 to 20% rubber	AR-4000 plus 18 to 20% rubber	PG-76	Asphalt rubber
Content	-	-	8% to 10%	5.5% to 7.0%	8% to 10%
Fiber Content	-	-	-	0.2% to 0.5%	-
Aggregate Properties					
Specific gravity	-	-	-	-	-
Water absorption	-	-	-	-	-
Sand equivalent	-	-	-		
Crushed faces	90% minimum	90% minimum	90% minimum	95% minimum 2 crushed faces for coarse aggregates (for crushed gravel)	95% minimum 2 crushed faces for coarse aggregates (for crushed gravel)
Flakiness index	-	-	-	-	-
LA abrasion test 100 revolutions	10% maximum	10% maximum	10% maximum	-	-
LA abrasion test 500 revolutions	40% maximum	40% maximum	40% maximum	30% maximum	30% maximum
Carbonates	-	-	-	-	-

	California OGAC (12.5-mm NMAS)	California RAC-O (12.5-mm NMAS)	California RAC-O-HB (12.5-mm NMAS)	Texas OGAC (12.5-mm NMAS)	Texas A-R OG (12.5-mm NMAS)
Soundness	-	-	-	20% maximum ($MgSO_4$)	20% maximum ($MgSO_4$)
Flat and elongated particles				5:1 ratio; 10% maximum	5:1 ratio; 10% maximum
Volumetric Properties					
Compaction method	-		-	Gyratory compactor	Gyratory compactor
Air voids				-	-
Draindown	4.0 g from 4 kg aggregate sample	4.0 g from 4 kg aggregate sample	4.0 g from 4 kg aggregate sample	20% maximum	20% maximum
VFA	-	-	-	-	-

Table 8: Characteristics of Open-Graded Mixes in the United States with 12.5-mm NMAS, Part 2 (New Jersey MOGAC, Alabama PMOGAC, Nevada OGAC)

	New Jersey MOGAC (12.5-mm NMAS)	New Jersey MOGAC (12.5-mm NMAS)	Alabama PMOGAC (12.5-mm NMAS)	Nevada OGAC (12.5-mm NMAS)
Gradation (mm)				
25.00 mm (1 in.)	-	-	-	-
19.00 mm (3/4 in.)	100	100	100	-
12.50 mm (1/2 in.)	85 to 100	90 to 100	90 to 100	100
9.50 mm (3/8 in.)	35 to 60	65 to 85	40 to 70	90 to 100
4.75 mm (No.4)	10 to 25	15 to 25	5 to 30	35 to 55
2.36 mm (No. 8)	5 to 10	5 to 10	4 to 12	-
2.00 mm (No. 10)	-	-	-	-
1.18 mm (No. 16)	-	-	-	5 to 18
425 µm (No. 40)	-	-	-	-
75 µm (No. 200)	2 to 5	2 to 4	3 to 6	0 to 4
Asphalt Binder				
Grade	PG 64-22	PG 76-22	Polymer-modified PG 76-22	AC 2.5, AC-5, AC-10, AC-20, AC-20P, AC-30, AC-40
Content	5.7% minimum	5.7% minimum	4.7 to 9%	-
Fiber Content	0.4% for mineral fibers; 0.3% for cellulose fibers	0.4% for mineral fibers; 0.3% for cellulose fibers	0.3% minimum	-
Aggregate Properties				
Water absorption	1.7% maximum	1.7% maximum	-	4% maximum
Sand equivalent	-	-	-	-
Crushed faces	-	-	-	90% minimum 2 faces
Flakiness index	-	-	-	-
LA abrasion test 100 revolutions	-	-	-	-
LA abrasion test 500 revolutions	40% maximum	40% maximum	48% maximum; 55% maximum for blast-furnace slag and sandstone	37% maximum
Carbonates	30% maximum	30% maximum	-	-
Soundness	10% maximum (Na_2SO_4)	10% maximum (Na_2SO_4)	10% maximum (Na_2SO_4)	12% maximum (Na_2SO_4)
Specific gravity	-	-	-	2.85 maximum
Flat and elongated particles	4:1 ratio; 7% maximum	4:1 ratio; 7% maximum	5:1 ratio; 10% maximum 3:1 ratio; 20% maximum	-
Volumetric Properties				
Compaction method	-	-	-	-
Air voids	20%	18%	12% minimum	-
Draindown	-	-	0.3% by BMTP-386	-
VFA	-	-	-	-

Table 9: Characteristics of Open-Graded Mixes in the United States with 19-mm and 25-mm NMAS

	Indiana OGAC (25-mm NMAS)	Indiana OGAC (19-mm NMAS)
Gradation (mm)		
37.5 mm (1 ½ in.)	100	-
25.00 mm (1 in.)	70 to 98	100
19.00 mm (3/4 in.)	50 to 85	70 to 98
12.50 mm (1/2 in.)	28 to 62	40 to 68
9.50 mm (3/8 in.)	15 to 50	20 to 52
6.3 mm (1/4 in.)	-	-
4.75 mm (No.4)	6 to 30	10 to 30
2.36 mm (No. 8)	15 ± 8	15 ± 8
2.00 mm (No. 10)	-	-
1.18 mm (No. 16)	2 to 18	2 to 18
600 µm (No. 30)	1 to 13	1 to 13
300 µm (No. 50)	0 to 10	0 to 10
150 µm (No. 100)	0 to 9	0 to 9
75 µm (No. 200)	0 to 8	0 to 8
Asphalt Binder		
Grade / Content	PG / 3% minimum	PG / 3% minimum
Fiber Content	-	-
Aggregate Properties		
Water absorption	5% maximum	5% maximum
Sand equivalent	-	-
Crushed faces	-	-
Flakiness index	-	-
Flat and elongated particles at 5:1	60% maximum	60% maximum
LA abrasion test 100 revolutions	-	-
LA abrasion test 500 revolutions	40% maximum	40% maximum
Soundness	12% maximum (Na_2SO_4)	12% maximum (Na_2SO_4)
Specific gravity	-	-
Volumetric Properties		
Compaction method	Gyratory compaction	Gyratory compaction
Air voids	15 to 20%	15 to 20%
Draindown	30% maximum	30% maximum
VFA	-	-

3 EUROPEAN POROUS ASPHALT CONCRETE MIX DESIGNS

Traffic noise has been a major concern in Europe where residential developments are next to highways and transportation lines. The European Union implemented policies that require noise mitigation through the use of quieter pavements, instead of sound walls, where noise abatement is necessary. Each European country establishes its own guidelines for selecting surface types based on comparative noise levels (20). Porous asphalt has been used extensively as a quiet pavement type to reduce traffic noise. This chapter explains the European Standard for porous asphalt and the adapted standards for Switzerland, Ireland, the United Kingdom, The Netherlands, and Sweden.

3.1 European Standard for Porous Asphalt

The European Standard for porous asphalt is specified in document *prEN 13108-7: Bituminous Mixtures—Material Specifications—Part 7: Porous Asphalt (PA),* which is a semifinal formal draft published in August 2001 (21). Each European country should adopt mixes according to these specifications.

According to this standard, binder for porous asphalt should be paving-grade or modified asphalt. The gradation requirement of the target composition of the mix is specified in terms of maximum and minimum percentages of the mix passing sieves 1.4 D, D, 2 mm, and 0.063 mm (D is the upper sieve size of aggregate in the mixture). The ranges between the maximum and minimum values should be selected from Table 10. As can be seen from the table, one or two additional sieves between D and 2 mm and one additional sieve between 2 mm and 0.063 mm can be specified.

Table 10: Gradation Ranges According to European Standard

Sieve (mm)	Ranges (percentage by mass)
D*	10.0
Optional sieves (one or two) between D and 2 mm	10.0 to 20.0
2 mm	0.0 to 7.0
Optional sieve between 2 mm and 0.063 mm	4.0 to 15.0
0.063 mm	1.0 to 5.0

* D is the upper sieve size of aggregate in the mixture, in millimeters.

D should be selected from the following sieves belonging to basic sieve set plus set 1 or 2:

- Basic sieve set plus set 1: 4 mm, 5.6 mm, 8 mm, 11.2 mm, 16 mm, 22.4 mm
- Basic sieve set plus set 2: 4 mm, 6.3 mm, 8 mm, 10 mm, 12.5 mm, 14 mm, 16 mm, 20 mm

A combination of these sieve sizes is not allowed. The optional additional sieves between D and 2 mm should be selected from the same sieve set from which D was selected, and the optional sieve between 2 mm and 0. 063 mm should be selected from the following sieves: 1 mm, 0.5 mm, 0.25 mm, and 0.125 mm. The European basic sieve size set along with the basic set plus set 1 and 2 are summarized in Table 11.

Table 11: European Sieve Sizes for Specifying Aggregates

Basic Set (mm)	Basic Set plus Set 1 (mm)	Basic Set plus Set 2 (mm)
0	0	0
1	1	1
2	2	2
4	4	4
-	5.6 (6)	-
8	-	6.3 (6)
-	8	8
-	11.2 (11)	10
-	-	-
-	-	12.5 (12)
16	16	14
-	-	16
-	22.4 (22)	20
31.5 (32)	31.5 (32)	-
-	-	31.5 (32)
-	45	40
-	63	-
63		63

The maximum and minimum percentages of aggregate passing sieves 1.4 D, D, 2 mm, and 0.063 mm should follow Table 12 when basic sieve set plus 1 or basic sieve set plus 2 are used.

Table 12: Grading of Target Composition—Basic Sieve Set plus Set 1 or 2, According to European Standard

Sieve (mm)	Aggregate Passing (percentage by mass)
D	To be specified by designer
1.4 D	100.0
D	90.0 to 100.0
2	5.0 to 20.0
0.063	2.0 to 10.0

The European Standard requires the minimum binder content to be between 3.0 and 7.0 percent by mass and the air-void content to be between 14 and 30 percent. Specimens should be compacted by the Marshall hammer impact compactor (100 blows) or gyratory compactor PCG3 (40 gyrations). The method of specimen preparation should be specified in the mix design procedure. Water sensitivity should be determined from the minimum indirect tensile strength ratio (ITSR), which is the ratio of the strength in the wet condition to the strength in the dry condition. For porous asphalt, ITSR should range between 50 and 100 percent. The water sensitivity test is conducted according to European test method EN 12697-12.

The European Standard also requires a test to determine the maximum particle loss of porous asphalt mixes, to evaluate the abrasiveness of the mix. Particle loss is calculated by the loss of mass of the mix in the Los Angeles (LA) machine (Cantabro wear test). Loss should be in the range of 10 to 50 percent by mass. A binder drainage test is also required for porous asphalt mixes. It is conducted using the drainage basket method for conventional mixes and the Schellenberg method for porous mixes with fibers, according to EN 12697-18. There is no specified range for the binder drainage value. The European Standard requires specification of either minimum horizontal or minimum vertical permeability of porous asphalt mixes in the mix design procedure. Permeability is determined in the lab by a constant-head permeameter, and minimum permeability should be in the range of $0.1 * 10^{-3}$ to $4 * 10^{-3}$ m/s.

If paving-grade binder is used, the mixing temperatures at any place in the mixing plant should be within the limits given in Table 13.

Table 13: Mixing Temperature Limits of Porous Asphalt Mixture, According to European Standard

Paving Grade of Binder (penetration at 25°C)	Temperature (ºC)
35/50	150 to 180
40/60	150 to 180
50/70	145 to 175
70/100	140 to 170
100/150	130 to 160
160/220	130 to 160
250/330	120 to 150

To prevent overspecification or a contradictory specification, one of the three combinations given in Table 14 should be used to specify an individual porous asphalt mixture.

Table 14: Possible Combinations of Requirements to Specify Porous Asphalt Mixtures According to European Standard

Requirement	Requirement Combination		
	1	2	3
Binder content	*	*	*
Aggregate gradation	*	*	*
Minimum void percentage	*		
Maximum void percentage	*	*	*
Horizontal permeability		*	
Vertical permeability			*
ITSR	*	*	*
Particle loss	*	*	*

* Indicates inclusion in specification.

Table 15 summarizes the European Standard requirements for specific tests.

Table 15: Characteristics of Porous Asphalt Mixes According to European Standard

Requirement	Range
Binder content	3 to 7% by mass
Aggregate gradation	Basic sieve set plus set 1 or 2
Minimum void percentage	14%
Maximum void percentage	30%
Horizontal permeability (minimum)	0.1 * 10^{-3} m/s to 4 * 10^{-3} m/s
Vertical permeability (minimum)	0.1 * 10^{-3} m/s to 4 * 10–^{3} m/s
ITSR	50%
Particle loss	10 to 50%

3.2 Switzerland

The latest version of the Swiss porous asphalt standard was prepared according to European Standard prEN 13108-7 (August 2001) (22). Porous asphalt can be used as the surface or base layer for roads, public areas, and airports. A special type of porous asphalt layer is called the drainage layer, and it is placed only as a surface layer in tunnels. Table 16 shows the asphalt mixes used for different pavement layers and the desired thickness of each asphalt type. The numbers listed for each porous asphalt (PA) mix designate the maximum aggregate size (in mm) of the mix.

Table 16: Asphalt Mixtures for Different Layers and Recommended Thicknesses in Switzerland

Asphalt Mixture Designation	Recommended Thickness (mm)
Surface Layer	
PA 8	25 to 35
PA 11	35 to 50
Base Layer	
PA B 16	40 to 80
PA B 22	60 to 150
Drainage Layer	
PA S 16	40 to 80
PA S 22	60 to 150
PA S 32	80 to 200

For surface and base layers, polymer-modified or special asphalt is specified, while for the drainage layer and for surfaces without traffic conventional asphalt can be used. Table 17 shows the binder recommendations for different porous asphalt concrete mixes.

Table 17: Binder Recommendations for Porous Asphalt Concrete Mixes in Switzerland

Binder Type	Asphalt Mix Type		
	PA (surface layer)	PA B (base layer)	PA S (drainage layer)
Bitumen			
50/70			O
40/100			+
Polymer Modified and Special Bitumen			
PmB 30/50-65 E	O	O	
PmB 50/70-65 E	+	+	O
PmB 70/100-60 E	+	+	O
Special bitumen	O	O	O

+: Used under normal conditions.
O: Used when traffic is present.

In addition to polymer, mineral or organic fibers and rubber can be added to the asphalt mix. Aggregate gradation is based on EN 13043 and can be 0/4, 4/8, 8/11, 11/16, 16/22, and 22/32 (0/4 shows the minimum and maximum aggregate gradations). Aggregate gradation specifications for surface-, base-, and drainage-layer porous asphalt concrete mixes are given in Table 18.

Table 18: Aggregate Gradations for Porous Asphalt Concrete Mixes in Switzerland

Sieve Size	Percentage Passing						
	Surface Layer		Base Layer		Drainage Layer		
	PA 8	PA 11	PA B 16	PA B 22	PA S 16	PA S 22	PA S 32
45.0							100
31.5				100		100	90 to 100
22.4			100	90 to 100	100	90 to 100	-
16.0		100	90 to 100	-	90 to 100	-	-
11.2	100	90 to 100	-	15 to 35	-	15 to 65*	15 to 60*
8.0	90 to 100	20 to 40	15 to 35	-	15 to 60*	-	-
5.6	-	-	-	-	-	-	-
4.0	15 to 35	-	-	-	-	-	-
2.0	10 to 17	8 to 15	7 to 14	6 to 13	7 to 20	6 to 20	5 to 20
0.5	4 to 10	4 to 10	4 to 10	4 to 10	4 to 10	4 to 10	4 to 10
0.063	3 to 5	3 to 5	3 to 5	3 to 5	3 to 5	3 to 5	3 to 5

* Differs from the European Specification.

When determining the binder content of the mixes, traffic and climatic conditions are considered. Table 19 shows the recommended minimum binder content of the porous asphalt mixes. This binder content is based on aggregates with a density of 2.65 Mg/m^3. If the density of the aggregates is different than this value, the minimum binder content should be corrected by a factor of α, which is given by the following equation:

$\alpha = 2.65/\rho$
where ρ is the density of the aggregate.

Table 19: Asphalt Binder Content for Porous Asphalt Mixes in Switzerland

Asphalt Mix	Binder Content
PA 8	≥5.0
PA 11	≥4.0
PA B 16	≥4.0
PA B 22	≥3.5
PA S 16	≥3.5
PA S 22	≥3.0
PA S 32	≥3.0

Specimens should be compacted by the Marshall hammer (100 blows). The recommended air-void content of the porous asphalt mixes is given in Table 20. Horizontal or vertical permeability can be specified instead of air-void content.

Table 20: Air-Void Content of Porous Asphalt Mixes in Switzerland

Asphalt Mix	Air-Void Content (%)
PA 8	≥20
PA 11	≥22
PA B 16	≥22
PA B 22	≥22
PA S 16	≥18
PA S 22	≥18
PA S 32	≥18

Water sensitivity of porous asphalt mixes is determined by the ITSR. The ITSR should be at least 70 percent for surface and base porous asphalt layers, and 80 percent for drainage porous asphalt layers.

If paving-grade binder is used, the temperature of the mixture in the mixing plant should be within the limits given in Table 21. If polymer or special bitumen is used, temperatures should be as provided by the supplier.

Table 21: Mixing Temperature Limits of Porous Asphalt Mixes in Switzerland

Paving Grade of Binder (1/10 mm)	Mixing Temperature (ºC)
50/70	145to 175
70/100	140 to 170

3.3 Ireland

The Irish porous asphalt surface course is normally placed on an impervious surface that has sufficient crossfall and longitudinal gradients to allow water removal from the surface. The porous asphalt mix should have a nominal maximum aggregate size (NMAS) of 14 mm and polymer-modified binder (22). Thickness of the porous asphalt layer ranges between 40 and 50 mm. The porous surface layer is bonded to the layer below the surface with a polymer-modified bonding coat.

Target binder content is determined from the binder drainage test using the basket method. Binder content is defined as the value 0.3 percent less than that at which 0.3 percent binder drainage occurs. At the target binder content, the porous asphalt mixture should also satisfy the requirements of the Cantabro wear test. The maximum allowed mass loss by the Cantabro wear test is 25 percent at 18ºC and 20 percent at 25ºC. Inorganic or organic fibers can be used to help prevent binder drainage. Properties of the polymer binder used in porous asphalt mixtures are given in Table 22.

Table 22: Properties of Polymer-Modified Porous Asphalt Binder for Mixes in Ireland

Property	Specified Value
Penetration at 25ºC to 0.1 mm	65 to 105
Softening point (ºC)	>70
Fraass brittle point (ºC)	<–15
Storage stability, ºC difference in softening point, top to bottom, after 4 days at 160ºC	<5
Resistance to hardening (rolling thin-film oven test) mass change (percent) Retained penetration (percent) Softening point increase (ºC) Softening point decrease (ºC)	<1.0 >60 <8 <2

The coarse aggregate used in porous asphalt mixes should consist of crushed rock or crushed gravel. Fine aggregates can be crushed rock fines, natural sands, or a mixture of both. Coarse aggregate properties are given in Table 23.

Table 23: Properties of Coarse Aggregates for Porous Asphalt Mixes in Ireland

Property	Category
Polished stone value (PSV)	>60
Resistance to fragmentation (LA test)	<25%
Aggregate abrasion value (AAV)	<10%
Flakiness index (10 to 14 mm fraction)	<15%
Flakiness index (6.3 to 10 mm fraction)	<20%

At least 2 percent by mass of the total aggregate should be hydrated lime filler. Hydrated lime should contain at least 90 percent calcium and magnesium hydroxide. The aggregate gradation and tolerances for target grading are given in Table 24.

Table 24: Target Aggregate Gradation and Permitted Tolerances for Porous Asphalt Mixes in Ireland

ISO Sieve (mm)	Percent Passing (%)	Tolerances for Target Grading
20	100	
14	95 to 100	
10	55 to 75	± 10
6.3	15to 25	± 4
2	10 to 17	
0.063	4 to 5.5*	

* Includes 2 percent hydrated lime by mass of the total aggregate.

The Irish mix design specifies a hydraulic conductivity test for porous asphalt mixes in the field. The relative hydraulic conductivity of the material is measured by a falling-head permeameter after the mix has cooled to ambient temperature and before trafficking. Outflow time is defined as the time elapsed for an outflow of 2 liters of water through the permeameter. Hydraulic conductivity is the reciprocal of the outflow time. To determine the hydraulic conductivity, five consecutive permeability measurements are taken at 20m intervals in the near-side wheel track of each lane of a highway and averaged. The average value of the hydraulic conductivity measurements should not be less than 0.12 s^{-1}, and each single value should not be less than 0.08 s^{-1}.

No compaction methods are specified; however, the specimen compaction procedure should be such as to provide a maximum air-void content of 28 percent. A water sensitivity test, to determine the ITSR, is also required for porous asphalt mixes. ITSR should not be less than 75 percent. Required design tests for Irish porous asphalt are given in Table 25.

Table 25: Required Design Tests for Porous Asphalt Mixtures in Ireland

Design Test	Parameter	Performance Level	Applicability of Test
Binder drainage test at 170ºC	Drainage characteristics of the binder from asphalt mixture	Target binder content	Design and quality control
Percent air voids	Void content	Maximum air-void content 28%	Design
Relative hydraulic conductivity	Measurement of water outflow under specific conditions	Relative hydraulic conductivity average 0.12 s^{-1} (minimum value 0.8 s^{-1})	Design and quality control
Water sensitivity test	Tensile strength test in accordance with IS EN 12697 Parts 12 and 23	ITSR (ratio of wet to dry) 75%	Design
Cantabro wear test	Percent loss	Mass loss < 25% at 18ºC (20% at 25ºC)	Design

3.4 United Kingdom

Porous asphalt mixes in the United Kingdom are placed 45 to 55 mm thick, and they are placed over an impermeable layer to protect underlying layers from the penetration of water (24). A 60-mm dense layer is required beneath the porous asphalt layer. An emulsion or a polymer-modified bond should be applied between the porous surface and the underlying layer.

A polymer modifier or fiber additive is specified to reduce draindown of porous asphalt mixes. Target binder content is specified as 4.5 percent by mass of the total mix. Target binder content is determined by a binder drainage test according to BS DD 232. A minimum of 2 percent hydrated lime by mass of the total aggregate is specified to help prevent binder stripping. The hydraulic conductivity of the porous asphalt layer should be between 0.12 and 0.4 s^{-1}.

Coarse aggregates used in porous asphalt mixes should be crushed rock or steel slag, while fine aggregate should be crushed rock fines, steel slag, natural sand, or a blend. Gravel is not allowed for porous mixes. Properties of coarse aggregates are given in Table 26.

Table 26: Properties of Coarse Aggregates for Porous Mixes in the United Kingdom

Property	Category
Resistance to fragmentation (LA test)	<30%
AAV	<12%
Flakiness index	<15

The aggregate gradations of UK porous asphalt mixes are given in Table 27.

Table 27: Aggregate Gradation for Porous Mixes in the United Kingdom

Sieve (mm)	Percentage by Mass of Total Aggregates Passing
31.5	100
20	95 to 100
14	55 to 75
6.3	20 to 30
2	5 to 10
0.063	3.5 to 5.5

3.5 The Netherlands

3.5.1 Single-Layer Porous Asphalt

The Dutch porous asphalt mix is primarily composed of gap-graded aggregates that are bonded together by a polymer-modified binder (25). Porous asphalt concrete acts as a lateral drain and hence improves water drainage and skid resistance. Another advantage of these mixes is their noise-reduction properties. They provide 3-dB (A) noise reduction compared to dense surfaces.

Porous asphalt concrete consists of crushed stones between 6 and 16 mm, crushed sand between 2 and 0.063 mm, and filler containing 25 percent $Ca(OH)_2$ with a size less than 0.063 mm. Specimens should be compacted by the Marshall hammer (2 * 50 blows). Air-void content should not be less than 20 percent. Penetration of the bitumen used for these mixes is 70/100. Bitumen content is specified as 4.5 percent by mass of the aggregates. Aggregate gradation of Dutch porous mixes is given in Table 28.

Table 28: Aggregate Gradation for Single-Layer Porous Asphalt Mixes in The Netherlands

Sieve Size	Desired Percentage Passing	Percentage Passing
16.0 mm		93 to 100
11.2 mm		70 to 85
8.0 mm		35 to 50
5.6 mm		15 to 30
2.0 mm	15.0	
0.063 mm	4.5	

The Netherlands requires a rotating surface abrasion test, indirect tensile strength test, semicircular bending test, and Cantabro wear test to be conducted on the porous asphalt mixes.

3.5.2 Double-Layer Porous Asphalt

The Netherlands also uses recently developed double-layer porous asphalt, in which a thin layer of porous asphalt is placed over a layer with coarse single-graded aggregate (26). This type of porous asphalt is used mainly on low-speed roads. Most common constructions of double-layer porous asphalt use a 25-mm top layer with a gradation of 4/8, meaning that aggregates are between 4 and 8 mm, and a 45-mm bottom layer with a gradation 11/16. An alternative construction method uses a 20-mm top layer 20 with a gradation of 2/6 and a 50-mm bottom layer with a gradation of 11/16.

Since the top layer has a fine gradation, porosity should be kept as high as possible and flow resistance as low as possible. To achieve this, the sand fraction is eliminated from the mixture and a high-viscosity material such as rubberized bitumen is used to compensate for the lack of sand. This high viscosity also enables use of higher binder content (6.5 percent) without causing a drop in binder draindown during warm weather. Rubberized bitumen is also used in the bottom layer to increase its service life.

Double-layer porous asphalt reduces noise levels 5 to 6 dB (A) compared to dense-graded surfaces.

3.6 Sweden

Sweden uses two aggregate gradations for porous asphalt: one with an NMAS of 11 mm and the other with an NMAS of 16 mm (27). Aggregate gradations of both mixes are given in Table 29.

Table 29: Aggregate Gradation for Porous Asphalt Mixes in Sweden

Sieve Size (mm)	Percentage Passing	
	ABD 11	ABD 16
31.5	-	100
22.4	100	98 to 100
16	98 to 100	85 to 99
11.2	85 to 99	40 to 60
8	20 to 51	20 to 41
5.6	15 to 31	10 to 28
4	10 to 24	8 to 24
2	8 to 17	7 to 17
1	5 to 13	6 to 13
0.5	5 to 9	4 to 10
0.25	3 to 7	3 to 7
0.125	2 to 6	2 to 6
0.063	2 to 5	2 to 5

Properties of aggregates used in porous asphalt mixes are given in Table 30.

Table 30: Properties of Aggregates for Porous Asphalt Mixes in Sweden

Property	Traffic Volume (ADT/lane * 1,000)			
	0.5 to 1.5	**1.5 to 3.5**	**3.5 to 7.0**	**>7.0**
Flakiness index	≤20	≤20	≤15	≤15
Crushed faces*	$C_{50/10}$	$C_{50/10}$	$C_{50/10}$	$C_{50/10}$
Aggregate wearing test (microdeval)	≤14	≤10	≤7	≤7
LA abrasion test (500 revolutions)	≤25	≤25	≤20	≤20

*$C_{50/10}$: 50 percent crushed, 10 percent uncrushed, and 40 percent half crushed and half uncrushed.

Binder content ranges of porous asphalt mixes are given in Table 31.

Table 31: Binder Content for Porous Asphalt Mixes in Sweden

Binder Type	Binder Content Range	
Penetration Grades	**ABD 11**	**ABD 16**
70/100	5.5 to 7.0	5.5 to 6.5
100/150	5.4 to 6.9	5.4 to 6.4
160/220	5.3 to 6.8	5.3 to 6.3

Sweden specifies cellulose fibers 0.3 to 1.0 percent by mass of the mix. Wetfix is added to the mix for adhesion purposes. Sweden also specifies minimum and maximum thicknesses for porous mixes. Thickness of the ABD 11 mix ranges between 24 and 44 mm, and thickness of the ABD 16 mix ranges between 36 and 64 mm. Air-void content ranges between 16 and 21 percent depending on the binder type and gradation. Table 32shows the specified air-void content for porous asphalt mixes.

Table 32: Air-Void Content

Binder Type	Air-Void Content (%)	
	ABD 11	**ABD 16**
70/100	16 to 20	15 to 19
100/150	17 to 21	16 to 20
160/220	17 to 21	16 to 20

4 SUMMARY

In the United States, open-graded mixes are placed mainly to improve permeability and hence wet-weather friction, while the main reason to place open-graded mixes in Europe is to benefit from their noise-reduction properties. In general, the porous mixes in Europe have higher air-void contents, ranging between 20 and 25 percent, while the open-graded mixes in the United States have air-void content of less than 20 percent. A horizontal or vertical permeability is specified in Europe; the United States has no specifications for minimum permeability values. Both Europe and the United States specify a maximum particle loss of 50 percent from the LA abrasion test. The tensile strength ratio is generally specified for porous mixes in Europe, and it should be at least 50 percent. However, only a few U.S. states specify a tensile strength ratio, and the required value is usually above 80 percent.

Swiss, UK, Irish, and Swedish standards confirm the European Standard. Since the mix design specifications in The Netherlands is not known, whether The Netherlands conforms to the European Standard was not evaluated.

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