REVIEW   **Open Access**

Review of porous asphalt pavements in cold regions: the state of practice and case study repository in design, construction, and maintenance

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Abstract

Porous asphalt pavement is a sustainable infrastructure tool used to benefit urban resilience. This paper summarizes the design, construction, and maintenance practices of porous asphalt pavements (PAPs) specific to cold regions. It includes discussions on the structural design considering frost depth and frost heave of subgrade soils, material selection and design for adequate freeze-thaw durability, construction of PAPs in cold weather, winter maintenance of PAPs for snow and ice control, and performance deterioration caused by other winter activities such as studded tires. Distinguished from other review works on this topic, the major contributions of this review paper employ case studies of PAPs to address design, construction, and maintenance concerns of PAPs in cold regions. These projects have demonstrated the success of using PAPs in cold regions and design practitioners can refer to these case studies for the new design and installation of PAPs in cold regions.

Keywords: Porous asphalt pavement, Cold regions, Design, Winter maintenance, Case study

Introduction

Permeable pavement is a unique class of pavement that functions as both a structural vehicular and pedestrian surface, but also as a stormwater management tool to reduce surface runoff. The most common permeable pavements include Porous Asphalt Pavement (PAP), Pervious Concrete (PC), Permeable Interlocking Concrete Pavement (PICP), and plastic grid-stabilized systems, however, a variety of proprietary options and related technologies also exist. The environmental and sustainable benefits of PAPs include, but are not limited to, the reduction of storm runoff volume, recharge of groundwater, improved water quality, and improvement of driving safety and quality by reducing hydroplaning tendency and noises [6, 63]. In cold regions, case studies
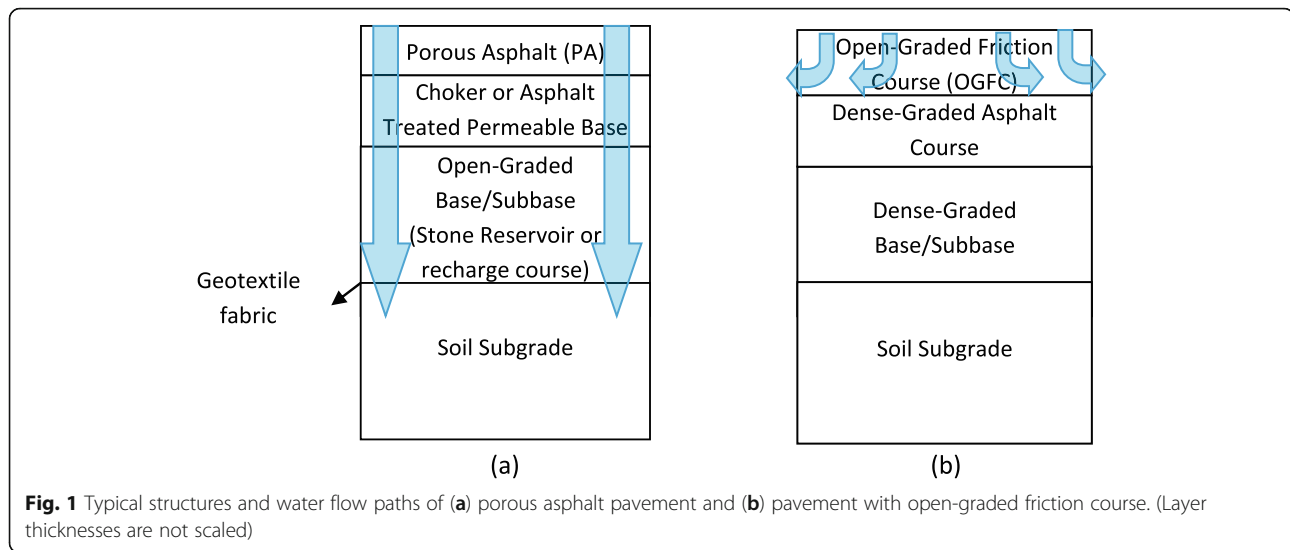
showed that PAPs had a faster snow melting rate than impermeable pavements and could prevent formation of black ice on pavement surfaces, which help reduce the use of salt in winter maintenance [23, 32, 50, 57, 64]. The reduction of ice build-up improves driving safety and transportation resilience after snowstorms along with lessening environmental impacts of excess salt application. With these benefits, PAP is considered as a green infrastructure technique to improve urban resilience [55] and has been used in various applications, such as parking lots, low-volume traffic roads, high-volume state routes, highway permeable shoulders, and permeable pavements at airports.

The PAPs are designed to allow water to flow through the full depth of the pavement into soil subgrade and/or underdrain pipes. A typical PAP structure with the water flow pathway is illustrated in Fig. 1a consisting of a porous asphalt (PA) surface course, a bedding course, and a stone reservoir course (aka stone recharge bed) often

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Fig. 1 Typical structures and water flow paths of (**a**) porous asphalt pavement and (**b**) pavement with open-graded friction course. (Layer thicknesses are not scaled)

placed over the geotextile fabric and uncompacted or lightly compacted soil subgrade (after [6]). This full-depth permeable pavement structure is designed to have different water flow pathways from pavements with open-graded friction course (OGFC) as shown in Fig. 1**b**, which consists of a permeable wearing OGFC mixture laid on the top of a dense-graded asphalt, base layer, and compacted subgrade. Although these two types of pavement have different pavement structures and water flow paths, the asphalt mixtures (PA and OGFC mixtures) used as wearing courses are similar.

Despite PAPs categorized as a low impact development technology for stormwater management, not all sites are suitable to install PAPs. The constraints include local regulatory requirements, geotechnical risks (e.g. Karst area, sinkholes, expansive soil), minimum depth to bedrock or seasonal groundwater table, groundwater contamination risk (e.g. potential chloride contamination due to the application of salt for deicing), and subgrade soil properties [6, 21]. The checklist developed by ASCE [6] shows the common design considerations for permeable pavements, which could be reviewed by designers in the feasibility study phase. In addition, a feasibility decision matrix was developed by Hein [21] to evaluate the suitability of PAPs as permeable shoulders. This decision matrix could be adapted by state and local agencies to evaluate the feasibility of PAPs for parking lots or residential streets as well, after adjustments of the design goals and weightings of design considerations.

In cold regions, additional considerations in design, construction, and maintenance of PAPs include (1) structure design with consideration of frost depth and frost heave of subgrade soils; (2) material selection and design for adequate freeze-thaw durability; (3) construction of PAPs in cold weather conditions, (4) winter maintenance of PAPs

for snow and ice control; and (5) pavement performance deterioration caused by winter activities such as plowing and use of studded tires. Therefore, this article mainly focuses on the syntheses and discussions on these topics and briefly summarizes the general guidelines for the design, construction, and maintenance of PAPs.

The objectives of this review article are to synthesize the state of practice and establish a case study repository of PAPs to address the above-mentioned concerns of design, construction, and maintenance of PAPs in cold regions. This review work searched database includes Transport Research International Documentation (TRID), American Society of Civil Engineers (ASCE) library, publications by National Asphalt Pavement Association (NAPA) and Federal Highway Administration (FHWA), standard specifications of northern States Departments of Transportation (DOTs) in the U.S., and Google Scholar. The literature searches and reviews mainly focus on the most recent 10-year publications (2010–2020) on PAPs in cold regions, albeit the earliest publication on PAPs cited in this paper is traced back to Thelen and Howe [57]. Distinguished from other literature review publications on PAPs in cold regions, e.g. Weiss et al. [63], the specific contribution of this review work uses 14 PAP projects, among which 12 projects are installed in cold regions, to illustrate state-of-practice on the design, construction, and maintenance of PAPs in cold regions. Engineering practitioners can refer to these case studies for the new design, installation, and maintenance of PAPs in cold regions.

Thickness design of porous asphalt pavements in cold regions

The thickness design of PAPs in cold regions includes considerations for hydrologic design, hydraulic design,

structural design, and base thickness verification with the frost depth requirements.

Hydrologic and hydraulic designs

The primary goal of the hydrologic design is to determine the peak flow rate (e.g. Rational method) or depth (e.g. Curve Number method) of the stormwater run-off so that the designed stone reservoir course has adequate thickness and storage capacity to retain the desired amount of stormwater temporarily. The stone reservoir is often designed to hold the respective stormwater, however, if flooding protection is a design requirement, then a larger storage volume may be required. The hydraulic design is primarily to estimate the drawdown time of the retained stormwater drain off from the stone reservoir course to the subgrade so that the designed PAP can restore capability for the consequent precipitation events. The drawdown time can be estimated based on the saturated flow theory [21] or unsaturated flow theory in soils [12]. The recommended requirements on drawdown time for PAPs range from 12[a], 24[b], or 48[c] to 72 h ([17] [a] [6]; [b] [63]; [c]). When the subgrade soil has a low permeability that leads to a longer drawdown time, underdrain pipes are designed and used for overflow control in a permeable pavement with partial-infiltration or no-infiltration to subgrade soils [6, 53]. The hydrologic and hydraulic designs and use of underdrain pipes can also prevent prolonged saturation and freeze-thaw damage of base and surface course in cold regions.

Structural design

The structural design of PAPs is conducted to determine the thickness of the PA course and verify the total thickness of the stone reservoir course and PA surface course is adequate to support designed traffic loads. The American Association of State Highway and Transportation Officials (AASHTO) empirical design method (aka AASHTO 1993 Design Method) is the most common method to design PAPs [63]. Schwartz and Hall [54] illustrate the design procedure and provide examples of using the AASHTO 1993 Design Method for PAPs.

The performance-based mechanistic-empirical design approach was also developed for PAPs [28, 33]. The catalog-type design procedure was developed to implement this design method and used to design the PAP parking lots in California State University, Long Beach Campus [51]. The designed PA parking lots have a 20 cm (7.9-in.) PA layer with a 5.1 cm (2-in.) choker layer and a 50 cm (19.7-in.) stone reservoir course.

Another pavement thickness design method to verify the structural sufficiency of PAP is the Soil Factor Design Method, which is mainly adopted by the Minnesota Department of Transportation (MnDOT) for the state-aid flexible pavement projects [67]. This method was used to design PAPs as Cells 86 and 88 in the MnROAD low-volume test road [32].

The asphalt-treated permeable base (ATPB) is an optional layer for a PAP. However, this asphalt-stabilized layer has a higher layer coefficient and structural strength than the unbounded choker layer or stone reservoir base. Therefore, an ATPB is often used in the PAP for driveways with the high-volume annual average daily traffic (AADT) to reduce the base thickness. For example, the PAP installed for the State Route 87 in Chandler, Arizona had a 15.2 cm (6-in.) PA wearing course, 15.2 cm (6-in.) ATPB, and 20.3 cm (8-in.) stone reservoir course, and used for AADT of 30,000 in the early of 1990s [24]. The PAP project installed for Maine Mall Road in South Portland, Maine, also used ATPB layer to increase the structural strength of the PAP with an AADT of 16,750 [44]. This PAP had a 7.6 cm (3-in.) PA wearing course, 15.2 cm (6-in.) ATPB, a minimum of 38.1 cm (15-in.) stone reservoir course, and 15.2–30.5 cm (6 to 12-in.) sand filter layer [44].

Design of porous asphalt pavement with frost depth requirements

PAP applications in cold climates are uniquely beneficial for the protection of permafrost, however, susceptible to frost damage from the direct introduction of water into the pavement base structure. The symptoms of pavement distress due to the frost damage include frost heave of the subgrade, significant loss of supportive strength of the thawed subgrade, and the consequent performance deteriorations in terms of cracking and raveling in pavements. The frost damage occurs when all of three necessary conditions exist simultaneously, which include (1) presence of water in the subgrade, (2) frost-susceptible soil, and (3) frost depth of sub-freezing temperatures (lower than 0 °C (32 °F)) exceeding the thickness of pavement to subgrade [60]. For PAPs, the presence of water in the subgrade is difficult to avoid and limits the primary benefit, as the stormwater is designed to infiltrate into the subgrade that is even likely saturated. The design of PAPs shall focus on the conditions of frost-susceptible soils and frost depth. Schwartz and Hall [54] listed the frost potential of different soil types, varying from non-frost-susceptible soil to very high frost-susceptible soil that should be replaced. Extreme caution must be exercised to design PAPs in the areas where the frost-susceptible subgrade soils exist and historically cause frost damages for impervious pavements.

To avoid the third necessary condition in terms of frost depth, the principle is to design the pavement with adequate layer thicknesses, including surface, base, and subbase (if used), to meet the frost depth requirement. There are two design guidelines used for PAPs to meet

this requirement. One is to strictly follow the principle that the total designed thickness of the pavement exceeds the local frost depth. This guideline becomes debatable, as several PAPs, which have the total designed thickness much lower than the local frost depth but exhibited no frost damages in cold regions [17]. Thus, the second design guideline recommends the total thickness of PAP above the subgrade shall exceed 65% of the local frost depth [59].

Table 1 summarizes four PAPs with the reported data of pavement structure, frost depth, frost heave, and early pavement performances, which are used to assess design guidelines of frost depth for PAPs. The consensus observations were that the frost depth was shallower in a PAP than the corresponding impermeable pavement during the freezing periods. When the air temperature warmed up during the thawing periods, the subgrade soils beneath a PAP thawed earlier and faster than soils beneath impermeable pavements [8, 23]. For the PAP installed in Luleå, Sweden, the subgrade soil was frost-susceptible, and the measured frost depth exceeded the pavement structure, which caused frost heave. However, the PAP exhibited lower and uniformly distributed frost heave (1–2 cm) than the frost heave (7–8 cm) in the impermeable pavement during the extremely cold winter [8]. The frost heave was lower in the thicker PAP with a base thickness of 100 cm (39.4-in.) than that was measured in the PAP with a base of 60 cm (23.6-in.). For MnROAD test sections, the measured frost depth also exceeded total pavement thickness, which caused noticeable seasonal heave. While for the PAP parking lot installed at Durham, New Hampshire, USA, and the PAP residential streets installed at Robbinsdale, MN, USA, the measured maximum frost depth was lower than or close to the thickness of PAP so that there was no visually observed frost heave. Based on these case studies, it concludes that the PAP has a low risk of frost damage due to lower frost depth and heave. It is advisable to recommend that in the areas with extreme or high frost-susceptible soils (e.g. PAP in Luleå, Sweden), the total designed thickness of the pavement shall be adequate to exceed or close to the local frost depth. Otherwise, the design guideline of the total thickness of PAP exceeding 65% of the local frost depth could be used [6].

Materials selection for porous asphalt pavement in cold regions

Subgrade soils

The types of subgrade soil greatly affect the performance of PAPs in cold regions, although PAPs have been successfully implemented in most soil types, including clays with low permeability and high frost-susceptibility. As shown in Table 1, PAPs installed in the MnROAD and Robbinsdale, MN, USA explored the influence of subgrade soil types, sand and clay, on the frost depth and structural supports. The PAP installed on the sandy subgrade had a shallower frost depth than that on the clayed subgrade [32, 64]. This observation was mainly attributed to the higher permeability and pronounced effect of air insulation in the sandy subgrade. As a result, the PAP over the sandy subgrade exhibited more effectiveness on the ice control and snow melting than the PAP overlaid on the clayey subgrade [64]. The sandy subgrade had similar back-calculated stiffness as the clayey subgrade in spring and summer, while the clayey subgrade exhibited higher stiffness during the freezing seasons. However, the clayey subgrade had less structural support than the sandy subgrade, evidenced by the lower back-calculated resilient modulus of stone reservoir base and higher longitudinal strain responses [32].

Geosynthetics

The geosynthetic material, such as geotextile fabric, geogrid, and geomembrane, are placed individually or jointly between native soils (subgrade soil and/or excavated soil) and stone reservoir course for different purposes in different applications. The non-woven geotextile fabric is used in the full-infiltration or partial-infiltration design for filtering purposes to prevent sediment-laden runoff from subgrade and/or excavated soils contaminating and clogging the stone reservoir course [17, 21]. In cold regions, a graded filter blanket is recommended to replace geotextile fabric to serve as a filtering and capillary barrier to mitigate frost damage [59].

The geogrid is used to stabilize subgrade soil and distribute loads uniformly over the structurally weak soils [6]. The use of geogrid can also reduce the thickness of PAPs [43] and increase the life of PAPs that are built over the saturated and uncompacted subgrade soils [20]. The geogrid and non-woven geotextile fabric could be used together, such as the PAP project at the Cuyahoga Valley National Park, Ohio, USA [65]. This PAP has a 7.6 cm (3-in.) PA, 5.1 cm (2-in.) choker with No. 57 limestones, and 22.9 cm (9-in.) stone reservoir layer, which was overlaid on the top of a geogrid and nonwoven geotextile fabric. Another PAP project that used geotextile fabric and geogrid jointly was installed in Decatur Street, Olympia, Washington. The geogrids were placed at the top and bottom of a 30.5 cm (12-in.) stone reservoir course to meet the designed equivalent single axle loads (ESALs) requirement [20].

A geomembrane is an impermeable material, which is used for the no-infiltration design of the permeable pavements to prevent runoff from entering into the subgrade and/or excavated soils. The no-infiltration permeable pavements are used in areas with expansive soils or high-potential frost susceptibility soils [6, 21]. The typical material of a geomembrane includes polyvinyl chloride

Table 1 Case studies of the porous asphalt pavements monitored with frost depth

Project Location	Luleå, Sweden	Durham, NH, USA	Albertville, MN, USA		Robbinsdale, MN, USA	
Year of Construction	1993/1994	2004	2008/2009		2009/2010	
Application	Residential Street	Parking Lot	MnROAD Low-Volume Road Test Loop		Low-volume residential Intersections	
Comparison with Impermeable Pavement	Yes	Yes	Yes		Yes	
Pavement Structure	4.5 cm PA	10.2 cm PA	15.2 cm PA		10.2 cm PA	
	3 cm Choker	10.2 cm Choker	10.2 cm Choker (RailRoad Ballast)		5.1 cm Choker	
	60 cm or 100 cm Stone Reservoir with underdrain pipes	61 cm Filter Course	25.4 cm Stone Reservoir (Crushed CA-15)		30.5 cm Stone Reservoir with 15.2 cm overflow draintile below the top of the reservoir	
		53.3 cm Stone Reservoir with 15.2 cm underdrain pipes				
	Geotextile	Geotextile	Geotextile &vertical plastic barriers		geotextile	
Total Thickness	67.5 cm or 107.5 cm	134.7 cm	50.8 cm		45.8 cm	
Subgrade Soil	Silty Moraine (Frost Susceptible)	Combination of infill and hydrologic soil group C soils	Sand (Cell 86)	Clay (Cell 88)	Sand (41st Ave. North)	Clay (27th Ave. North)
Permeability of Subgrade Soil	0.06 to 2.4 mm/min.	0.025–0.24 mm/min. (Hydrologic Group C Soils, [17])	Highly drainable (Not tested)	0.16 mm/min.	> 0.63 mm/min.	Not Reported
Year/Max. Frost Depth	1994/95: 110 cm	03/2005: 30.5 cm	11/2010–04/2011: 61–91.4 cm	11/2010–04/2011: 91.4–121.9 cm	> 43.2 cm (43.2 cm is the lowest temperature testing location)	
	1995/96: 140 cm	01–03/2006: 24.4 cm				
		11/2006–04/2007: 69.9 cm				
		11/2007–04/2008: 34.3 cm				
Frost Heave	Uniformly distributed 1–2 cm for 100 cm Base 4–8 cm for 60 cm Base	Not visually observed	Appeared to heave seasonally noted by MnROAD personnel		Not Reported	
Pavement Early Distresses	No observed frost damage due to irregular frost heave	Sharp steel edges of snowplows;	minor surface raveling; higher rut depth; no visible cracks;		No visual distress	Some signs of excess binder
Resources	Bäckström [8]	Briggs [9]	Lebens and Troyer [32]		Wenck Associates [64]	
		Holue [23]	Weiss et al. [62]		Weiss et al. [62]	
		Roseen et al. [49]				
		Roseen et al. [50]				

(PVC), ethylene propylene diene monomer (EPDM), or high-density polyethylene (HDPE) [21]. The project installed at Sylvan Avenue, City of Ann Arbor, Michigan, is a no-infiltration PAP design. This project used an impervious PVC fabric over the clayed subgrade to direct stormwater into a manhole to resolve water ponding and icing problems on the pavement surface [27]. The designed PAP has a 7.6 cm (3 in.) PA, a 45.7–61.0 cm (18–24 in.) stone reservoir course, a woven geotextile fabric, and a 15.2 cm (6 in.)-thick sand filter layer with underdrain pipes overlaid on an impervious PVC liner.

Stone reservoir aggregates

The aggregate used for the stone reservoir course shall be selected to fulfill the hydrologic and structural requirements to retain the stormwater runoff and support traffic loads. The freezing damage of aggregate is minimal because the water in the stone reservoir course freezes rarely, and in case this happens, the large voids in the stone reservoir course provide spaces for water expansion without causing damage [57].

Choker aggregates

The choker course (aka bedding course) is designed to interlock large stone reservoir aggregates and provide a smooth and stable platform for PA placement. Table 2 shows four projects with choker thickness and combinations of aggregates used for the choker and stone reservoir course. The typical thickness of the choker course is 5.1 cm (2-in.), while Hansen [17] and Minnesota Asphalt Pavement Association (MAPA) [36] recommend a 1-in. thickness of the choker layer. The No. 57 aggregate is recommended to use as the choker aggregate when No. 3 aggregate is used for stone reservoir course [17, 63].

Asphalt treated permeable base (ATPB)

The asphalt treated permeable base (ATPB) is a viable bedding course to substantially increase the structural loading capacity and provide a stable platform for PA construction. Table 3 shows the synthesis of specifications on ATPB from northern DOTs, including Minnesota (Section 2363), Pennsylvania (Section 360), Missouri (Section 302), New York (Section 401), and Oregon (Section 00743), and general specification provisions by American Public Works Association, Washington State, Local Agency General Specification Provisions [5], and a project-based specification. The No. 57, No. 67, or similar gradation is commonly used as the aggregate gradation in an ATPB mixture. The APTB mixture is designed with lower asphalt binder content (typically 2.0–4.5%) than the PA mixture (typically 6.0–6.5%). Thus, ATPB works as a cost-effective practice to reduce the total thickness of a PAP [43] and is typically used for the high-volume traffic road, such as projects of the State Route 87 in Chandler, Arizona [24] and Maine Mall Road in South Portland, Maine [44].

The performance grade of the asphalt binder used in an ATPB mixture varies in specifications. The polymer-modified asphalt binder is increasingly used in the ATPB mixture. The binder content varies from 2.0% to 4.5%, which should uniformly coat on aggregates at a minimum percentage of 90% or 95% tested using the AASHTO T195 and has no excessive binder drained off from aggregates. The specification on the use of warm mix additive and/or recycled materials (e.g. reclaimed asphalt pavement and recycled asphalt shingle) in the ATPB mixture also differs among the state agencies and shall conform to the local experience.

Moisture stripping of ATPB might be a concern when it is used as a drainable base that is placed over an

Table 2 Selection of aggregate size for choker course

Project Location	Denver, Colorado, USA	Robbinsdale, MN, USA		Calgary, AB, Canada	Long Beach, CA, USA
Year of Construction	2008	2009/2010		2011	2019
Application	Parking Lot	Low-volume residential Intersections		Drive Lane	Parking Lot
Pavement Structure	6.4 cm PA	10.2 cm PA		8.0 cm PA	20 cm PA
	5.1 cm Choker (AASHTO No.67)	5.1 cm Choker (12.5 mm Crushed Stone)		7.0 cm Choker (12.5 mm gravel)	5 cm Choker (ASTM No.8)
	17.8 cm Stone Reservoir (No.3 Aggregate)	30.5 cm Stone Reservoir (38.1 mm −63.5 mm Granitic Stone)		50 cm Stone Reservoir (63 cm Gravel)	50 cm Stone Reservoir (ASTM No.2)
	2.5 cm Sand Cushion				
	15.2 cm filter layer (ASTM C-33 Sand)				
	Geotextile fabric & Impermeable plastic liner	Geotextile fabric		Geotextile fabric	Geotextile fabric
Subgrade Soil	No infiltration to subgrade	Sand (41st Ave. North)	Clay (27th Ave. North)	Low Infiltration Soil (0.58 mm/h)	Lean Clay to Clayey Sand
Resources	Piza and Eisel [46]	Wenck Associates [64]		Huang [26]	Saadeh et al. [51]

Table 3 Specifications for Mix Design of Asphalt Treated Permeable Base in the Northern States

Sieve Size		MnDOT (2018) [37]		PennDOT (2016) [45]	MoDOT (2018) [38]		NYSDOT (2018) [40]		ODOT (2018) [42]	APWA-WA-LAGSPs [5]	Maine Mall Project [44]
		PASS RC	PASB		Grade 4A (No.57)	Grade 4B (No.67)	1	2			
		% Passing by Weight									
2″	50 mm	–	–	–	–	–	100	100	–	–	–
1.5″	37.5 mm	–	100	100	100	–	95–100	75–100	–	–	100
1″	25 mm	–	95–100	95–100	95–100	100	80–95	55–80	99–100	–	95–100
3/4″	19 mm	100 (5/8″)	85–95	–	–	90–100	–	–	85–95	100	80–95
1/2″	12.5 mm	85–100	–	35–65	25–60	–	30–60	23–42	35–68	90–100	35–70
3/8″	9.5 mm	50–100	30–60	–	–	20–55	–	–	–	40–80	–
No.4	4.75 mm	0–25	–	12–24	0–10	0–10	10–25	5–20	2–10	0–30	2–10
No. 8	2.36 mm	0–5	0–10	6–16	0–5	0–5	3–15	2–15	0–5	0–20	0–5
No. 16	0.3 mm	–	–	–	–	–	–	–	–	0–10	–
No. 30	0.6 mm	–	0–5	–	–	–	–	–	–	–	–
No. 200	0.075 mm	–	0–3	0–5	–	–	0–4	–	0–2	–	0–2
Asphalt Binder Performance Grade		PG 64S-22		PG 64–22	PG 64–22, PG70–22, PG 76–22		–		–	PG 70–22ER	PG76–28 with SBS polymer
Recommended Binder Content (%)		–		2.0–3.0 (initial 2.5)	2.5%		2.0–4.0	2.5–4.5	2.5–3.5	3.0–4.5	2.0 Min.
Min. Percent Coating on Aggregate (%)		–		95%	–		–		90%	–	95%

impermeable layer [18, 61]. The extended saturation due to the non-functional drainage and lower binder content in ATPB are the main causes of the moisture stripping. However, PAPs allows the water to drain off promptly from the ATPB course to the stone reservoir course and subgrade soils, which minimizes the saturation and stripping potentials of ATPB. The addition of a liquid anti-stripping additive or hydrated lime can help to mitigate moisture damage of ATPB mixtures. In the worst scenario that an ATPB mixture experiences moisture stripping in PAPs, it would degrade as an unbound open-graded choker and can still maintain the hydrologic performance, since the aggregate gradation (No.57 or No. 67) in an ATPB mixture is similar to choker aggregate gradation.

Porous asphalt

The mix design of a PA mixture generally follows the design guidance of the OGFC mixture where primary concerns include draindown stability and rapid oxidation. Tables 4 and 5 summarize aggregate quality requirement and mixture design of PA based on national design guidelines from NAPA publication [29] and ASTM D7064/D7064M-08 [7], as well as design guidance of PA mixtures in cold regions from state agencies [42, 45], a state asphalt pavement association [36], a local general special provisions [5], the research university [59], and a project-based design provision [44]. The aggregate quality tests generally include the Los Angeles abrasion test, fractured faces, flat and elongated particles, durability, and soundness test. The PA mixture is typically designed with the binder content higher than 5.5%, air voids higher than 16%, and binder draindown less than 0.3%. The typically designed number of gyrations (N_{des}) for the PA mixture is 50.

The moisture susceptibility owing to freeze-thaw cycles is one of the durability concerns for PA mixtures

Table 4 Aggregate Quality Requirements for Porous Asphalt Mixture

	Aggregate Property	NAPA IS 115 (2002) [29]	ASTM D7064/D7064M-08 [7]	Oregon Department of Transportation (ODOT) [42] a	Pennsylvania Department of Transportation (PennDOT) [45]	Minnesota Asphalt Pavement Association (MAPA) [36] c	UNHSC [59]	Maine Mall Project [44]
Coarse Aggregate	LA Abrasion (AASHTO T96; ASTM C131)	≤30%	≤30%	≤30%	≤ 35%–45%b	≤ 35%	≤ 40%	Mico-Deval ≤18% (AASHTO TP 58–99)
	Soundness Test (AASH TO T 104)	–	–	Sodium Sulfate Test	–	Magnesium Sulfate Test	–	–
	Fractured Faces (AASH TO T335; ASTM D5821)	One Face: 100% min.	One Face: 95% min.	One Face (No.8): 75 min.	One Faceb: 55–100 min.	One Face: 55 min.	One Face: 90% min.	One Face: 100% min.
		Two Faces: 90% min.	Two Faces: 90% min.	Two Faces (>No.4): 90 min.	Two Facesb: 80–100 min.		Two Faces: 75% min.	Two Faces: 90% min.
	Flat and Elongated Particles (ASTM D4791)	5:1 ratio: ≤ 5%	5:1 Ratio: ≤ 10%	5:1 Ratio: ≤10%	5:1 Ratio: ≤ 10%	5:1 Ratio: ≤ 5%	3:1 ratio: ≤ 8%	5:1 ratio: ≤ 5%
		3:1 ratio: ≤ 20%						3:1 ratio: ≤ 20%
	Absorption (AASHTO T85)	< 2% (Preferred)	–	–	–	≤ 2%	–	–
	Voids in Coarse Aggregate (VCA): VCAmix < VCAdrc (AASHTO T19)	Yes	Yes	–	–	Yes	–	Yes
Fine Aggregate	Angularity (AASHTO T304)	≥ 45	≥ 40	–	≥ 40–45%b	–	–	≥ 45
	Sand Equivalent Test (AASHTO T176)	–	≥ 45%	≥ 45%	≥ 40–50%b	–	–	≥ 50%
	Plasticity Index (AASHTO T90)	–	–	0 or Non-Plastic	–	≤ 4 (Mineral Filler)	≤ 6 (Passing No.40)	≤ 4 (Mineral Filler)

aAdditional aggregate tests include durability tests for coarse aggregates (ODOT TM 208) and harmful substances (AASHTO T113)

bThe requirements depend on the ESAL

cAdditional aggregate requirements include clay content (AASHTO T 176) less than 30%, total spall in fraction retained on No. 4 Sieve less than 2.5%, spall content in total sample less than 2.5%, and percent slumps in fraction retained on No. 4 Sieve less than 0.5%

Table 5 Mix Design Guidance for Porous Asphalt Mixture

Sieve Size		NAPA IS 115 (2002) [29]	ASTM D7064/D7064M-08 [7]	Oregon Department of Transportation (ODOT) [42] 3/8"	1/2"	Pennsylvania Department of Transportation (PennDOT) [45] 3/8" Wear	Minnesota Asphalt Pavement Association (MAPA) [36]	APWA-WA-LAGSP S[5]	UNHSC [59]	Maine Mall Project (2010) [44] 3/8"	1/2"
		Aggregate Gradation Broadband Limits (Percent Passing by Weight)									
3/4"	19 mm	100	100	–	99–100	100	100	100	100	–	100
1/2"	12.5 mm	85–100	85–100	99–100	90–98	95–100	85–100	90–100	85–100	100	85–100
3/8"	9.5 mm	35–60 (55–75[a])	35–60	90–100	–	70–100	55–75	55–90	55–75	85–100	55–75
No.4	4.75 mm	10–25	10–25	22–40	18–32	20–40	10–25	10–40	10–25	20–40	10–25
No.8	2.36 mm	5–10	5–10	5–15	3–15	10–20	5–15	0–20 (No.40: 0–13)	5–12	5–10	5–10
No.200	0.075 mm	2–4	2–4	1–5	1–5	0–4	2–4	0–5	2–4	2–4	2–4
Asphalt Binder Performance Grade		Two grades stiffer than normal binder	One or two grades stiffer (high PG) than normal binder	Polymer modified asphalt binder for wearing course		PG 70–22 or PG 76–22	PG 58–28 or PG 64–22	PG 70–22ER or higher grade	PG64–28 SBR, PG 76–22, or PG 76–28 SBS	PG 76–28 SBS	
Binder Content (%) by Total Mix		6.0–6.5%	6.0–6.5%	Per JMF (ODOT TM 318)		5.5–7.0%	5.5% Min.	6.0–7.0%	5.8–6.5%	6.0% Min.	
Fiber Dosage (%) by Total Mix		0.3% Cellulose 0.4% Mineral	0.2–0.5%	–		0.2–0.4% Cellulose	0.2–0.4% Cellulose	based on draindown test	0.25%	0.3% Cellulose[c] 0.4% Mineral[c]	
Gyratory Level (Ndes)		50	50	3/8" mix: 50 (1/2" mix: non-SGC)		50	50	75	–	50	
Air Voids (ASTM D3203 or ASTM D6857)		≥ 18%	≥ 18%	16–20% (VFA: 30–50%)		16–20% (ASTM D6752) 18–22% (AASHTO T275 or T269)	≥ 16%	16–25%	16–22%	20%	
Cantabro Abrasion Unaged		≤ 20%	≤ 20%	–		–	–	–	≤ 20%	–	
Cantabro Abrasion Aged		≤ 30%	≤ 30% (Average) ≤ 50% (Any Individual)	–		–	–	–	≤ 30%	–	
Draindown (ASTM D6390)		≤ 0.3%	≤ 0.3%	70–80% (ODOT TM 318)		≤ 0.3%	≤ 0.3%	≤ 0.3%	≤ 0.3%	≤ 0.3%	
Moisture Susceptibility (AASHTO T283)		TSR ≥ 80% (5 FT cycles[b])	TSR ≥ 80% (5 FT cycles)	TSR ≥ 80% (for surrogate dense-graded mix)		Coating ≥90% (ASTM D3625) or surrogate dense graded mix	Not Applicable	Coating ≥95% (ASTM D3625) or surrogate dense graded mix	TSR ≥ 80% (1 FT cycle), otherwise, use anti-strip additive	–	

[a] Indicated in the Appendix B of NAPA IS 115 [29]

[b] Apply a vacuum of 87.8 kPa for 10 min to saturate the compacted specimens and conduct five freeze/thaw cycles

[c] Properties of cellulose fiber and mineral fiber are specified in detail

used in cold regions. The modified AASHTO T283 is typically used to determine the retained tensile strength of a PA mixture after five freeze-thaw cycles instead of one cycle. The tensile strength ratio (TSR) higher than 80% is used as the threshold value to control moisture damage of PA mixtures. In case the designed PA mixture fails to meet the moisture susceptibility requirement, a liquid anti-stripping additive and/or hydrated lime can be used to improve compatibility between aggregates and asphalt binder [7]. The polymer-modified asphalt binder is also recommended to use in cold regions to improve the freeze-thaw durability of PA mixtures [32, 52].

Another durability concern for a PA mixture is the raveling due to reductions of cohesive and adhesive strengths caused by the oxidization of asphalt binder. The Cantabro test is used to assess the PA mixtures' resistance to abrasion. The laboratory accelerated aging protocol includes 85 °C for 5-day aging [29] or 60 °C for 7-day aging [7] for the compacted PA specimens. The maximum mass loss values for unaged and aged specimens tested by the Cantabro abrasion test are 20% and 30%, respectively. The use of a polymer-modified asphalt binder and increasing the binder content are two effective practices to improve the durability and raveling resistance of PA mixtures [29]. However, such high binder content could lead to the binder draindown during the construction phase and summer seasons, which cause voids clogging and permeability declination at the lower part of mixtures [23, 69]. The addition of fiber in a PA mixture becomes a common

practice to minimize the binder draindown ([3, 19, 47]; and [68]), improve durability by allowing higher binder content [1, 14], and increase resistance to rutting and cracking of PA mixtures [1, 35].

Construction
Subgrade, geosynthetics, stone reservoir course, and choker
The preparations of subgrade, placement of geosynthetics, and installations of stone reservoir course and choker in cold regions follow the common construction guidance of permeable pavements in other areas. The details can be referred to the publication by ASCE [6].

ATPB and PA mixtures
The best practices of ATPB and PA installations in cold regions or under cold weathers are summarized in Tables 6 and 7 according to the construction sequences of ATPB and PA mixtures. The air and surface temperatures should be higher than 10 °C to place ATPB and PA mixtures ([45, 59], and [42]). This constrains the construction season of APTB and PA mixtures in cold regions. The warm mix asphalt technology can help to extend the paving season, allow long haul distance, and compact asphalt mixtures at lower temperatures than hot mix asphalt, which is recommended to use in cold regions. The silo storage time shall be minimal to reduce the oxidation of mixtures. When ATPB or PA mixture is placed, the thickness of one lift shall be less than 10.2 cm (4-in.), but higher than twice the maximum

Table 6 Construction requirements of the asphalt-treated permeable base in cold regions

Construction	Requirements
Weather and Site Conditions	• ≥ 10 °C (50 °F) [42]
Plant Mixing	• ≤ 177 °C (350 °F); mixing temperature range is determined based on the viscosity or recommended by asphalt binder supplier
Silo Storage	• ≤ 8 h [45] • ≤ 2 h [44]
Placement Thickness	• ≤ 10.2 cm (4-in.) ([38, 45], and [42]) • ≥ twice the maximum aggregate size in ATPB [42]
Roller Selection	• Steel-wheeled roller with a weight of 8–10 tons and operated using static mode with no vibration ([37, 45], and [40]) • Pneumatic tire roller is prohibited.
Rolling temperature	• 60–110 °C (140–230 °F) [40] • Sufficient cool but higher than 43.3 °C (110 °F) [37] or 37.8 °C (100 °F) [38]
Rolling pattern	• Two to four passes and avoid over-rolling • APWA-WA-LAGSPs [5]: low amplitude oscillatory rolling mode first to seat and static mode to smooth the surfaces; targeted air voids of 15–20% and minimum infiltration rate of 63 mm/min. (150 in./h) tested by ASTM C170.
Inspections	• Elevation, thickness, and smoothness requirements ([37] and [45])
Protections	• Free of contaminations; geotextile fabric can be used to cover the ATPB and maintain its cleanliness [17] • Traffic is not permitted on the ATPB course [45] • Traffic is allowed after a 72-h cure [42]
Tack Coat	• Not allowed on the newly-placed and clean ATPB course [5, 40] • Light tack coat (0.02 gal/yd^2 residual asphalt) may be used when the ATPB course is dirty [5]

Table 7 Construction requirements of porous asphalt in cold regions

Construction	Requirements
Weather and Site Conditions	• ≥ 10 °C (50 °F) [42, 45, 59] • ≥ 15.6 °C (60 °F) and do not place on raining days and over a wet surface [40]
Plant Mixing	• ≤ 177 °C (350 °F) (ODOT 2016) • Increase dry mixing time [40] and wet mixing time [29] when a fiber is used.
Silo Storage	• ≤ 4 h in the non-insulated silo and 8 h in the insulated silo [5] • ≤ 2 h in Maine Mall project [44] • ≤ 1.5 h in MnROAD test sections [32]
Hauling	• Haul vehicles with a clean and smooth dump bed coated with a non-petroleum asphalt release agent [29, 59] • Avoid long haul distance [59]; • WMA technology can be used to extend the paving season and allow long haul distance. • Avoid segregation when PA mixtures are deposited from haul vehicles [42]
Placement Thickness	• One lift for small projects [6] • Two lifts for thicker cross-section [6] or large projects in cold weathers [59] • ≤ 10.2 cm (4-in.) for one lift [42, 45] • ≥ twice the maximum aggregate size in PA for one lift [42]
Roller Selection	• Smooth double steel-wheeled roller with a weight of 8–10 tons [6, 17] • An additional small roller with a weight of 1–1.5 tons could be used for finishing rolling to achieve a smooth finished surface [6, 59] • The pneumatic-tired roller is prohibited ([29], [36], and [40])
Rolling temperature	• Sufficient cool to resist roller [42] and avoid over compaction [9] • UNHSC [59]: breakdown (135–162.8 °C (275 °F − 325 °F)); intermediate (93.3–135 °C (200 °F−275 °F)); finishing (65.6–93.3 °C (150 °F − 200 °F)); and cessation (79.4 °C (175 °F)). • Peabody [44]: intermediate (93.3–135 °C (200°F–275 °F)); intermediate (93.3–135 °C (200°F−275 °F)); and cessation (79.4 °C (175 °F)).
Rolling passes and patterns	• Hansen [17]: 2–4 passes • Peabody [44]: a minimum of 3 passes for the Maine Mall project • ASCE [6]: 2–3 passes • Minnesota Asphalt Pavement Association (MAPA) [36]: 1–2 passes • APWA-WA-LAGSPs [5]: use a density gauge to monitor in-place air voids during the compaction and decide the cessation of rolling • Pennsylvania Department of Transportation (PennDOT) [45]: construct two test sections to develop rolling patterns • New York State Department of Transportation (NYSDOT) [40]: construct a 1000 square feet test section to develop rolling patterns • Oregon Department of Transportation (ODOT) [42]: a minimum of four passes for breakdown and intermediate rolling and additional passes for finishing rolling
Joints	• Longitudinal joints: place adjacent lane with an overlap of the compacted lane by 2.5–5.1 cm (1–2 in.) [45]; staggered and offset at least 15.2 cm (6 in.) [42] • Transverse joints: Spray Type RS-1 or equivalent emulsified asphalt to achieve good bonding [59]
Inspections	• Smoothness, thickness, in-place air voids tested by density gauge [40] • Infiltration rate: ≥ 84.6 mm/min. (200 in./h) (Pennsylvania Department of Transportation (PennDOT) [45])); ≥ 42.3 mm/min. (100 in./h) [5]
Curing time before opening to traffic	• Cure at least 24 h ([17, 36], and [40]) • Cure at least 48 h [6, 59] • Cure at least 72 h [42]

aggregate size. The steel-wheeled roller is used and operated in a static mode to compact APTB and PA mixtures. Pneumatic tire roller is prohibited. The APTB or PA mixture shall be sufficiently cool and stable before compaction. The rolling pattern shall be developed to compact ATPB and PA mixtures in such a way as to achieve balanced hydraulic performance (higher voids are preferred) and mechanical strength (lower voids are preferred). A density gauge is recommended to monitor the in-place density and air voids during the compaction of the PA mixture and ensure to achieve balanced performances [69]. Adequate curing time is needed to cool down ATPB and PA mixtures before opening to traffic.

Maintenance

The maintenance for PAPs involves (1) corrective maintenance for distresses on pavement surfaces; (2) preventive and restorative maintenance for permeability, and (3) winter maintenance for snow and ice control in cold regions.

Corrective maintenance for surface distresses

The localized patch is commonly used to fix PA raveling in small areas, which is one of the typical PAPs' distresses as reported by Hossain et al. [24] and Lebens and Troyer [32]. Raveling is caused by many factors, such as materials (e.g. lower binder content, high air voids, and oxidation), construction (e.g. temperature segregation, insufficient compaction, and weak interface bonding between surface and underlying layers), and repetitive vehicle loads [13, 22]. When PA mixture is readily available, it is the preferred patching material to maintain hydraulic performance, especially when the patching area is larger than 10% of the permeable surface [17]. A dense-graded asphalt mixture is an alternative patching material for small areas. However, a dense-graded asphalt mixture is not recommended to patch at locations where the water flow will converge and not be able to flow around the patched areas [48].

Corrective maintenance is also needed to repair wearing damages caused by studded tires or snow chains in cold regions where they are allowed to use in winters. Al-Rubaei et al. [2] reported that studded tires created excessive fines to clog PAPs, but studded tire damage on PAPs is rarely reported in the literature. Since PAPs use the OGFC mixture as the surface course, this type of asphalt mixture is very susceptible to wearing damages caused by studded tires [34] and snow chains [4]. This was the reason that led to the discontinuity of using OGFC for high-traffic volume roads in cold regions, e.g. Washington [4] and Oregon [39]. One of the potential methods to reduce studded tire wearing on PAPs is to design PA mixtures using aggregates with larger size and

higher abrasion resistance [41]. Therefore, in cold regions, the volume of vehicles equipped with studded tires and snow chains should be considered as an additional factor in the feasibility study of a PAP project.

Preventive and restorative maintenances for clogged permeable surfaces

Preventive and restorative maintenances, such as mechanical sweeping, pressure washing, and vacuum sweeping, are used individually or jointly to restore the infiltration of clogged permeable surfaces due to debris (e.g. dust, sand, or vegetation) or debris-laden flow. Low infiltration can be also caused by improper mix design, over compaction, or surface densification (e.g. rutting). In these locations, preventive and restorative maintenances cannot restore the low infiltration.

Figures 2 and 3 illustrate the effectiveness of these maintenance methods on the permeability restoration of PAPs in short-term and long-term service life. Figure 2a shows the infiltration of PAPs in MnROAD test sections maintained by vacuum sweeping [32] and Fig. 2b shows two PAPs in Canada maintained by dry and wet vacuum sweeping [10], hand sweeping, pressure washing, and low/high suction vacuum sweeping ([16], and [15]). These projects showed that the infiltration rates of PAPs decreased dramatically in the early stage, even though vacuum sweeping and/or pressure washing are used, which could only restore the permeability of PAPs to a very limited extent.

However, these non-destructive maintenances are necessary to maintain the long-term infiltration performance of PAPs, which are demonstrated in Fig. 3 using two long-term PAP projects in northern Sweden. The PAP in Haparanda (Fig. 3a) was maintained by mechanical sweeping only without vacuuming, and the PAP in Luleå was maintained by the mechanical and vacuum sweeping and pressure washing to clean the applied fine gravel and dust after each winter until 2005/2006. Consequently, the high-pressure washing, vacuum sweeping, or combination of these two methods worked more effectively to restore permeability of PAP in Luleå than PAP in Haparanda in both 2011 and 2015 maintenances. Therefore, Al-Rubaei et al. [2] concluded that regular and sufficient maintenance is critical to retain the long-term permeability of PAPs. This conclusion is also applicable to maintain the long-term hydraulic performance of pervious concrete pavement [25].

When PAPs are severely clogged and non-destructive cleaning methods cannot restore the infiltration of PAPs to meet hydrologic design goals, the surface milling can be used as the restorative maintenance method. Typically, the milling depth is down to the choker layer and a new PA course is repaved [11]. The shallow milling was attempted and reported recently by Winston et al. [66], which is considered as a rational restorative method since
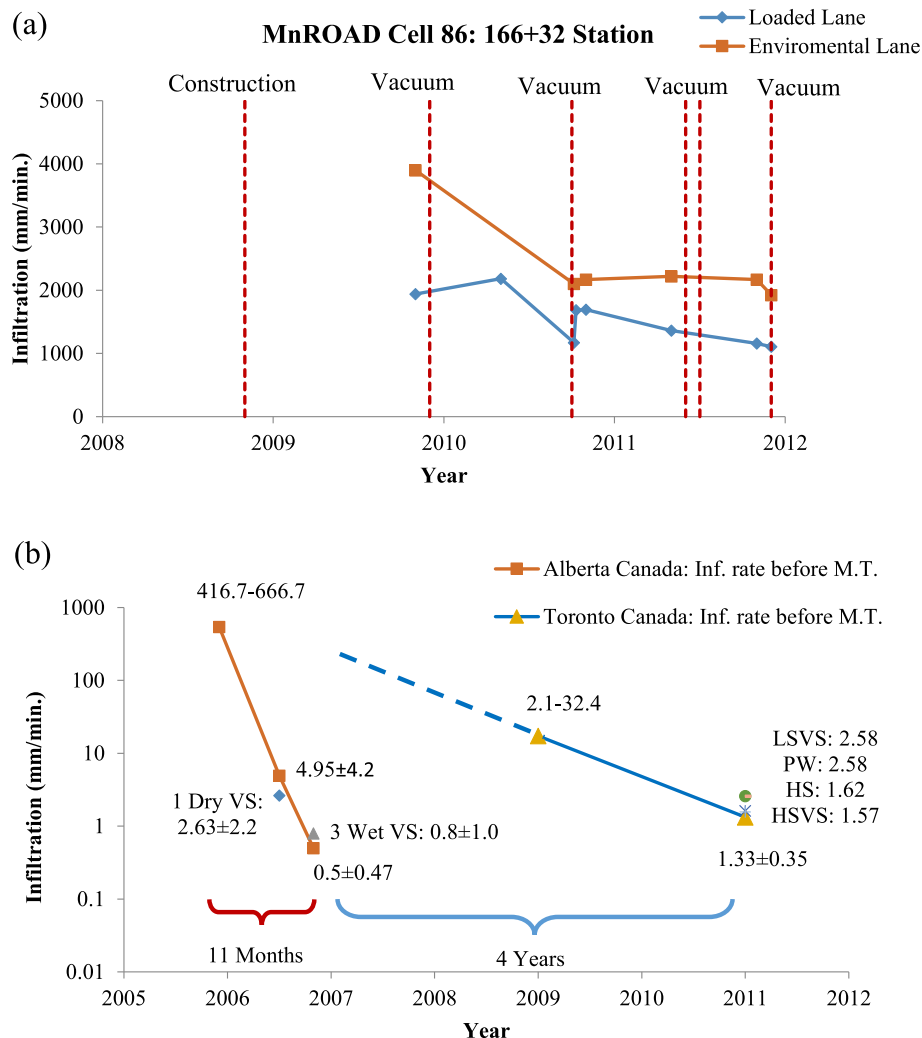
Fig. 2 Short-term infiltration rate and restorative maintenance for porous asphalt pavements at (**a**) MnROAD test sections, MN, USA [32] and (**b**) Alberta[1], Canada [10] and Toronto[2], Canada [15, 16]. (Acronym: Inf. = infiltration; M.T. = maintenance; VS = vacuum sweeping; HS = hand sweeping; PW = pressure washing; LSVS: low suction vacuum sweeping (airflow of 5.95 m³/min.); HSVS = high suction vacuum sweeping (airflow of 7.93 m³/min.)). [1]The infiltration rate of this project is calculated based on the average testing results along the center of the pavement. [2]The initial infiltration rate of this project is not available and the dashed line is extrapolated

the clogging materials are mainly accumulated on the top of permeable pavements [2]. Winston et al. [66] tested shallow milling at various depths of 0.5 cm, 1.5 cm, and 2.5 cm (0.2 in., 0.6 in., and 1 in.) for the PAP in Luleå, Sweden, which has a total thickness of PA surface of 4.5 cm (1.8-in.). The debris control and removal during and after the milling process are crucial to prevent the clogging of the milled surface. This study removed debris after milling using pressure washing. As shown in Fig. 3b, the shallow milling method was more effective than non-destructive cleaning methods to restore permeability, and the milling to the depth of 2.5 cm (0.6 in.) was the only restorative maintenance method that can restore the infiltration to the rate of this PAP when it was newly paved [66].

Winter maintenance

Winter maintenance treatments, such as sanding, snow plowing, and applications of anti-icing and deicing additives, are used to improve traction and eliminate snow and ice on pavement surfaces to provide safe driving conditions. Sanding is not recommended or even prohibited for PAPs [2, 6, 11, 17, 21], because the applied fine gravels or sands and their crushed products by vehicles can cause severe clogging and significant reduction of the surface permeability [2, 10, 15]. When sands have to be applied, it is recommended to use relatively large-size sands with minimal dust [2], and vacuum sweeping should be performed to remove sands and debris [6].
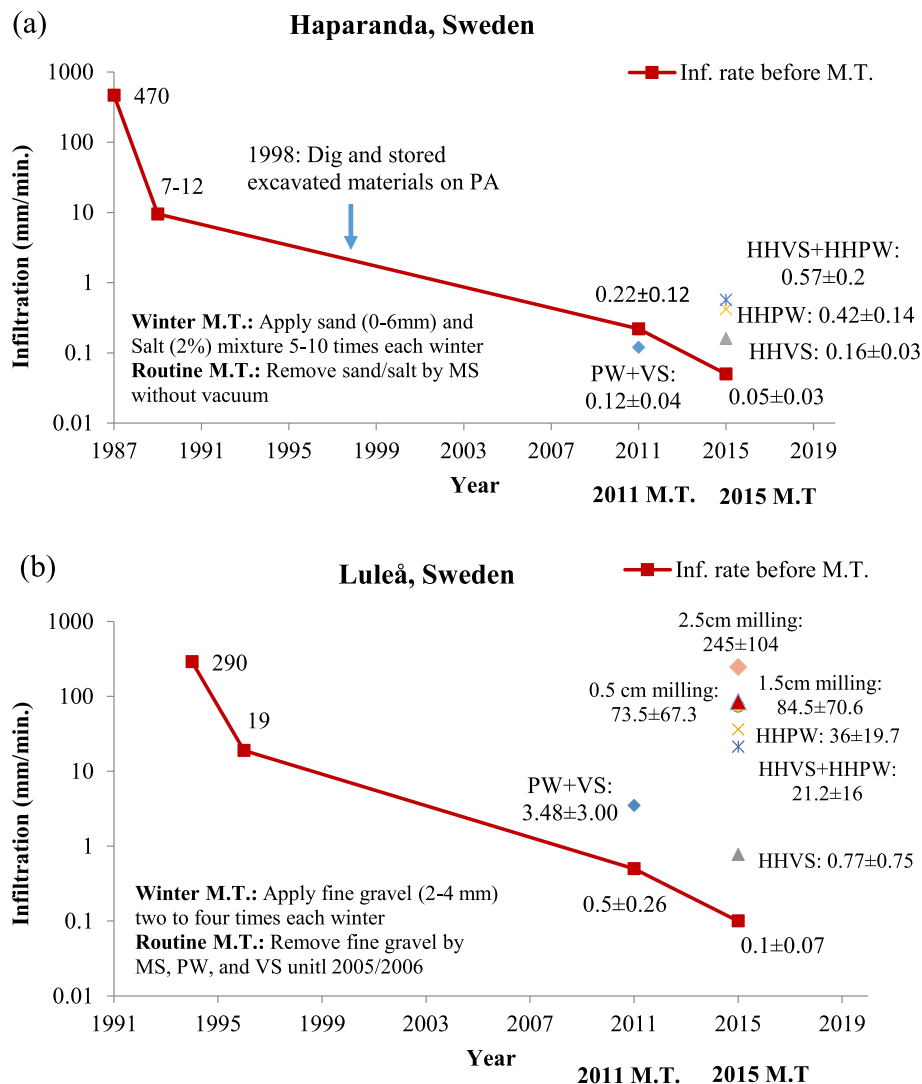
Fig. 3 Long-term infiltration rate and restorative maintenance for porous asphalt pavements at (**a**) Haparanda, Sweden [2, 66] and (**b**) Luleå, Sweden [2, 8, 56, 66]. (Acronym: Inf. = infiltration; M.T. = maintenance; MS = mechanical sweeping; PW = pressure washing; VS = vacuum sweeping; HHVS = hand-hold vacuum sweeping; HHPW = hand-hold pressure washing)

Mechanical sweeping without vacuuming should be avoided, because a regenerative street sweeper may spread out sands or debris over the permeable surfaces to cause further clogging [31].

The snow plowing is operated as routine practice for PAPs after snow events. However, plow damages on PAPs were reported by Briggs [9] and Lebens and Troyer [32]. Practices to reduce plow damages include the use of non-mental blades [11], the use of wide blades, avoidance of back-blading [30], and raise of the blade. However, Hein [21] mentioned special blades are not necessary, and UNHSC [58] did not recommend raise of blades. The plowed snow should not be piled on permeable pavements [11], because snow plowing also collects dust and debris

that can clog permeable pavements as snow melts [6]. In case the snow piling on permeable pavements is unavoidable, vacuum sweeping is recommended to clean the permeable surfaces after snow melts.

Salts are commonly applied on impermeable pavements before and after snowstorm events to control and reduce compacted snow and black ice. Application of salts has to be reduced for PAPs because salts can flow with snowmelt water and pollute underground water in full-infiltration and partial infiltration applications. Indeed, it is found that salts can be significantly reduced for winter maintenance of PAPs in cold regions. This conclusion is supported by case studies of the PAP parking lot in the University of New Hampshire (UNH)

Campus, and PAPs installed in Robbinsdale, MN. The UNH parking lot study tested various salt application rates on both PA and dense-graded asphalt parking lots. The statistical analysis indicated a salt reduction of 64%–77% on PAP was feasible to maintain equivalent or better surface conditions, which were quantified by the coverage area of snow and ice and pavement skid resistance [23, 50]. Wenck Associates [64] monitored and compared plowed but unsalted PAPs with plowed and salted/unsalted dense-graded asphalt pavements. It was found that the unsalted PAP had a comparable area of uncovered surfaces by snow and ice, but a few to several hours of time lag were observed between salted dense pavement and unsalted PAP, depending on the conditions of air temperature and solar radiation.

The salt reduction for PAPs could be attributed to two reasons at least. The first one is that the PAPs warm up more rapidly than the conventional asphalt pavement as air temperature increases [8, 50]. This leads to a faster snow melting rate on PAPs than conventional pavements, which was observed in MnROAD test sections, especially in the event of light snowfall followed by a sunny day [32]. The second attribution is that, except for freezing rain events, salts are not needed to prevent black ice on PAPs, because the melting snow and ice can drain off from PAPs promptly without standing water ([23, 57], and [50]). Thus, the PAP is a viable option to reduce salt application for winter road maintenance in cold regions.

Conclusions and recommendations

In cold regions, the PAP works as a green infrastructure tool to improve the resilience of cities and winter transportation systems. This paper synthesized case studies, literature, and specifications to address specific concerns of design, construction, and maintenance of PAPs in cold regions. These concerns include frost damages of PAPs, freeze-thaw durability of ATPB and PA mixtures, construction of PAPs in cold weathers, and maintenances of PAPs for permeability and snow and ice control in winters. The conclusions and recommendations include:

(1) Based on the established case study repository in this paper, the type of subgrade soil (sand or clay) greatly affects the structural and thermal performance of PAPs in cold regions. In general, PAPs exhibited a lower risk of frost damage than impervious pavements due to lower frost penetration depth and rapid response to warm air temperatures. In areas with low risks of frost damages, the design of the total thickness of PAP exceeding 65% of the local frost depth could be used. While in areas with high frost-susceptible soils, it is recommended to design the total thickness of PAP equivalent to the local frost penetration depth.

(2) The guideline of the mix design of PA mixture in cold regions is summarized in this work following the national design guidance, specifications of northern state DOTs and state asphalt pavement association in cold regions of the U.S., and research outcomes from universities. Generally, the use of polymer-modified asphalt binder with higher binder content and/or anti-stripping additives is recommended to improve the freeze-thaw durability and reduce the raveling of PA mixtures. Warm mix asphalt technology is also recommended for PA mixtures in cold regions. The uses of these additives increase the material and construction costs of PAPs. However, potential savings can be achieved from stormwater management, environmental benefits, and winter maintenance operations. Thus, the life cycle cost analysis for PAPs needs to be conducted with considerations of urban and transportation resilience benefits and impacts of climate change and extreme events, such as floods and snowstorms, on road infrastructures.

(3) Regular restorative maintenance methods, such as mechanical sweeping, pressure washing, and vacuum sweeping, can only restore the permeability of PAPs partially, but these practices are critical to maintain the long-term performance of PAPs and meet hydrologic design goals. Shallow surface milling is an emerging and promising method to effectively restore the permeability of PAPs, while methods of collection and cleaning of dust need to be developed to minimize clogging after shallow milling. Future works are also needed to explore other innovative design and cleaning methods for PAPs to maintain long-term permeability.

(4) Sanding should be prohibited for winter maintenance of PAPs. Snowplowing could be operated routinely after snow events. PAPs allow lower salts application for snow and ice control due to the rapid responses to ambient temperatures and prompt drainage of meltwater. To understand the fundamental mechanism of rapid responses to air temperature and fast thawing of snow and ice on PAP surfaces, research works are needed to develop theoretical analyses to investigate the internal heat transfer process in PAPs based on heat transfer and fluid flow in a porous medium.

Abbreviations
AADT: Annual Average Daily Traffic; AASHTO: American Association of State Highway and Transportation Officials; APWA-WA-LAGSPs: American Public Works Association, Washington State, Local Agency General Specification Provisions; ASCE: American Society of Civil Engineers; ASTM: American Society for Testing and Materials; ATPB: Asphalt-Treated Permeable Base; DOT: Department of Transportation; EPDM: Ethylene Propylene Diene Monomer; ESALs: Equivalent Single Axle Loads; FHWA: Federal Highway Administration; HDPE: High-Density Polyethylene; MAPA: Minnesota Asphalt Pavement Association; MnDOT: Minnesota Department of Transportation; MoDOT: Missouri Department of Transportation; NAPA: National Asphalt Pavement Association; NYSDOT: New York State Department of Transportation; ODOT: Oregon Department of Transportation; OGFC: Open-Graded Friction Course; PA: Porous Asphalt; PAPs: Porous Asphalt Pavements; PC: Pervious Concrete; PennDOT: Pennsylvania Department of Transportation; PICP: Permeable Interlocking Concrete Pavement; PVC: Polyvinyl Chloride; TRID: Transport Research International Documentation; TSR: Tensile Strength

Ratio; UNH: University of New Hampshire; UNHSC: University of New Hampshire Stormwater Center

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Afonso ML, Dinis-Almeida M, Fael CS (2017) Study of the porous asphalt performance with cellulosic fibres. Constr Build Mater 135:104–111
2. Al-Rubaei AM, Stenglein AL, Viklander M, Blecken G (2013) Long-term hydraulic performance of porous asphalt pavements in northern Sweden. J Irrig Drain Eng 139(6):499–505
3. Alvarez AE, Martin AE, Estakhri C (2011) A review of mix design and evaluation research for permeable friction course mixtures. Constr Build Mater 25(3):1159–1166
4. Anderson KJ, Uhlmeyer S, Sexton T, Russell M, Weston J (2013) *Evaluation of long-term pavement performance and noise characteristics of open-graded friction courses*. WA-RD 749.2. Washington State Department of Transportation, Olympia
5. APWA-WA-LAGSPs. (2016). American public works association, Washington State, Local Agency General Specification Provisions. https://www.wsdot.wa.gov/partners/apwa/Division_5_Page.htm
6. ASCE (2015) In: Eisenberg B, Lindow KC, Smith DR (eds) Permeable pavements. Permeable pavements task committee. American Society of Civil Engineers, Reston
7. ASTM D7064/D7064M-08 (2013) Standard Practice for Open-Graded Friction Course (OGFC) Mix Design. https://doi.org/10.1520/D7064_D7064M-08R13 American Society for Testing and Materials
8. Bäckström M (1999) *Porous pavement in a cold climate*. PhD dissertation. Luleå University of Technology, Luleå
9. Briggs JF (2006) *Performance assessment of porous asphalt for stormwater treatment*. Master thesis. University of New Hampshire, Durham
10. Brown CR (2007) *Characterization of solids removal and clogging processes in two types of permeable pavement*. Master thesis. University of Calgary, Calgary
11. Bruinsma J, Smith K, Peshkin D, Ballou L, Eisenberg B, Lurie C, Costa M, Ung C, Nassiri S, Shi X, Haselbach L (2017) Guidance for usage of permeable pavement at airports. The National Academies Press, Washington
12. Chai L, Kayhanian M, Givens B, Harvey JT, Jones D (2012) Hydraulic performance of fully permeable highway shoulder for storm water runoff management. J Environ Eng 138(7):711–722
13. Danish B (2018) Investigation of bonding between open graded friction courses and underlying asphalt pavement layers. Clemson University, Doctoral Dissertation https://tigerprints.clemson.edu/all_dissertations/2225
14. Decoene Y (1990) Contribution of cellulose fibers to the performance of porous asphalts. Transport Res Record 1265:82–86
15. Drake J, Bradford A (2013) Assessing the potential for restoration of surface permeability for permeable pavements through maintenance. Water Sci Technol 68(9):1950–1958
16. Drake J, Bradford A, Seters TV (2010) "Performance of permeable pavements in cold climate environments." in low impact development 2010: redefining water in the City, pp 1369–1378
17. Hansen K (2008) Porous asphalt pavements for stormwater management: design, construction and maintenance guide. Information series 131. National Asphalt Pavement Association, Lanham
18. Harvey J, Tsai B, Long F, Hung D (1999) *Cal/APT program - asphalt treated permeable base (ATPB)*. FHWA/CA/OR-99/09. California Department of Transportation, Sacramento
19. Hassan HF, Al-Oraimi S, Taha R (2005) Evaluation of open-graded friction course mixtures containing cellulose fibers and styrene butadiene rubber polymer. J Mater Civ Eng 17(4):416–422
20. Haub A, Tosomeen C (2008) Under-pavement infiltration demonstration - Decatur street low impact development roadway project. International Low Impact Development for Urban Ecosystem and Habitat Protection, Settle, pp 1–8. https://doi.org/10.1061/41009(333)26
21. Hein DK (2013) Permeable shoulders with stone reservoirs. Washington, DC: American Association of State Highway and Transportation Officials (AASHTO)
22. Hernandez-Saenz MA, Caro S, Arámbula-Mercado E, Martin AE (2016) Mix design, performance and maintenance of permeable friction courses (PFC) in the United States: state of the art. Constr Build Mater 111:358–367
23. Holue KM (2008) Winter performance assessment of permeable pavements: a comparative study of porous asphalt, pervious concrete, and conventional asphalt in a northern climate. In: Master thesis. University of New Hampshire, Durham
24. Hossain M, Scofield LA, Meier WR (1992) Porous pavement for control of highway runoff in Arizona: performance to date. Transport Res Record 1354:45–54
25. Hu N, Zhang J, Xia S, Han R, Dai Z, She R, Cui X, Meng B (2020) A field performance evaluation of the periodic maintenance for pervious concrete pavement. J Clean Prod 263:121463
26. Huang J (2015) Permeable pavement in cold climates: improving hydraulic and water quality performance. PhD dissertation. University of Calgary, Calgary
27. Jones, W. (2012). "Porous asphalt is key to integrated storm water management." Asphalt Magazine. http://asphaltmagazine.com/porous-asphalt-is-key-to-integrated-storm-water-management/
28. Jones D, Harvey J, Li H, Wang T, Wu R, Campbell B (2010) Laboratory testing and modeling for structural performance of fully permeable pavements. Research report. California Department of Transportation, Sacramento
29. Kandhal PS (2002) *Design, construction, and maintenance of open-graded asphalt friction courses*. Information series 115. National Asphalt Pavement Association, Lanham
30. Kevern J (2010) Operation and maintenance of pervious concrete pavements. Transp Res Board 11–0656. https://trid.trb.org/view/1091515
31. Knappenberger T, Jayakaran AD, Stark JD, Hinman CH (2017) Monitoring porous asphalt stormwater infiltration and outflow. J Irrig Drain Eng 143(8):04017027
32. Lebens MA, Troyer B (2012) Porous asphalt pavement performance in cold regions. Minnesota Department of Transportation, St. Paul
33. Li H, Jones D, Harvey J (2012) Development of mechanistic–empirical design procedure for fully permeable pavement under heavy traffic. Transport Res Record 2305:83–94
34. Li X, Zhang K, Bahadori A, Muhunthan B (2020) Modification of asphalt materials to resist studded-tire wear on pavements. J Mater Civ Eng 32(3):04020023
35. Ma X, Li Q, Cui YC, Ni AQ (2018) Performance of porous asphalt mixture with various additives. Int J Pavement Eng 19(4):355–361. https://doi.org/10.1080/10298436.2016.1175560
36. Minnesota Asphalt Pavement Association (MAPA). (2016). Draft guideline specification for porous or dense-graded asphalt pavement structures for

storm water management. https://cdn.ymaws.com/www.asphaltisbest.com/resource/resmgr/resources-engineering/tech_specifications/Draft-Porous-Spec-07-28-16.pdf

37. Minnesota Department of Transportation (MnDOT) (2018) Standard specifications for construction. Department of Transportation, St. Paul https://www.dot.state.mn.us/pre-letting/spec/2018/2018-spec-book-final.pdf

38. Missouri Department of Transportation (MoDOT). (2018). Missouri standard specifications for highway construction. https://www.modot.org/sites/default/files/documents/2018%20Missouri%20Standard%20Specific%20-%20MHTC%20%28July%202018%29.pdf

39. Muench ST, Weiland C, Hatfield J, Wallace LK (2011) Open-graded wearing courses in the Pacific northwest. SPR 680. Oregon Department of Transportation, Salem

40. New York State Department of Transportation (NYSDOT) (2018) Standard specifications: construction and materials. State of New York, Department of Transportation, Engineering Division, Albany https://www.dot.ny.gov/main/business-center/engineering/specifications/english-spec-repository/2018_1_specs_usc_tc.pdf

41. Niezgoda SL, Muszynski M, Navickis-Brasch A (2016) A critical review of permeable asphalt behavior and performance to guide application to arterial streets in cold climates. Conference World Environ Water Res Congress:70–80. https://doi.org/10.1061/9780784479865.008

42. Oregon Department of Transportation (ODOT) (2018) Oregon standard specifications for construction. Oregon Department of Transportation, Salem https://www.oregon.gov/ODOT/Business/Documents/2018_STANDARD_SPECIFICATIONS.pdf

43. Palmer, M. (2014). Porous asphalt: design and construction. Washington Stormwater Center. https://www.wastormwatercenter.org/wp-content/uploads/Module-3.3-Porous-asphalt-10-20-14-1-slide.pdf

44. Peabody D (2010) Performance of a porous pavement system on the Maine Mall Road in South Portland. Technical report 10-05. MaineDOT, transportation research division, Augusta

45. Pennsylvania Department of Transportation (PennDOT). (2016). Specifications. https://www.dot.state.pa.us/public/PubsForms/Publications/Pub_408/408_2016/408_2016_IE/408_2016_IE.pdf

46. Piza H, Eisel C (2011) Porous asphalt at Denver wastewater management building. Urbban Drainage and Flood Control District, Denver

47. Punith VS, Suresha SN, Raju S, Bose S, Veeraragavan A (2011) Laboratory investigation of open-graded friction-course mixtures containing polymers and cellulose fibers. J Transp Eng 138(1):67–74

48. Putman BJ (2012) Evaluation of Open-Graded Friction Courses: Construction, Maintenance, and Performance. FHWA-SC-12-04. South Carolina Department of Transportation, Columbia

49. Roseen RM, Ballestero TP, Houle JJ, Briggs JF, Houle KM (2012) Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. J Environ Eng 138(1):81–89

50. Roseen RM, Ballestero TP, Houle KM, Heath D, Houle JJ (2014) Assessment of winter maintenance of porous asphalt and its function for chloride source control. J Transp Eng 140(2):04013007

51. Saadeh S, Ralla A, Al-Zubi Y, Wu R, Harvey J (2019) Application of fully permeable pavements as a sustainable approach for mitigation of stormwater runoff. Int J Transport Sci Technol 8(4):338–350

52. Schaus LK (2007) Porous asphalt pavement designs: proactive design for cold climate use. Master thesis. University of Waterloo, Waterloo

53. Schwartz SS (2010) Effective curve number and hydrologic design of pervious concrete storm-water systems. J Hydrol Eng 15(6):465–474

54. Schwartz CW, Hall KD (2018) Structural design guidelines for porous asphalt pavements. Information series 140. National Asphalt Pavement Association, Lanham

55. Staddon C, Ward S, De Vito L, Zuniga-Teran A, Gerlak AK, Schoeman Y, Hart A, Booth G (2018) Contributions of green infrastructure to enhancing urban resilience. Environ Syst Decision 38(3):330–338

56. Stenmark C (1995) An Alternative Road Construction for Stormwater Management in Cold Climates. Water Science and Technology, 32(1):79–84.

57. Thelen E, Howe LF (1978) Porous pavement. The Franklin Institute Press, Philadelphia

58. UNHSC (2011) Winter maintenance guidelines for porous asphalt. University of new Hampshire Stormwater Center (NUHSC), Durham https://www.unh.edu/unhsc/sites/unh.edu.unhsc/files/docs/UNHSC%20porous%20winter%20maintenance%20fact%20sheet_1_11.pdf

59. UNHSC (2014) UNHSC design specifications for porous asphalt pavement and infiltration beds. University of New Hampshire Stormwater Center, Durham

60. U.S. Army Corps of Engieers (1984) Engineering and design: pavement criteria for seasonal frost conditions, mobilization construction. Engineering Manual No. 1110–3-138. Department of The Army Corps of Engineers, Office of the Chief of Engineers, Washington https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-3-138.pdf

61. Webb D, Sholar G, Musselman J, Upshaw P, Page G (2007) An evaluation of asphalt treated permeable base. Research report: FL/DOT/SMO/07–511. Florida State Material Office, Gainesville

62. Weiss PT, Kayhanian M, Khazanovich L, Gulliver JS (2015) Permeable pavements in cold climates: state of the art and cold climate case studies. Minnesota Department of Transportation, St. Paul

63. Weiss PT, Kayhanian M, Gulliver JS, Khazanovich L (2019) Permeable pavement in northern north American urban areas: research review and knowledge gaps. Int J Pavement Eng 20(2):143–162

64. Wenck Associates (2014) Porous pavement paired intersection study. Shingle Creek Watershed Management Commission and Minnesota Pollution Control Agency, Robbinsdale

65. Wilkerson, P. (2011). "Porous asphalt pavement seminar and demonstration: lessons learned". https://irp-cdn.multiscreensite.com/f2c35bed/files/uploaded/4PaulWilkerson-PorousAsphaltLessionsLearned2.pdf

66. Winston RJ, Al-Rubaei AM, Blecken GT, Viklander M, Hunt WF (2016) Maintenance measures for preservation and recovery of permeable pavement surface infiltration rate–the effects of street sweeping, vacuum cleaning, high pressure washing, and milling. J Environ Manag 169:132–144

67. Yang, M. (2020). Flexible Pavement Design Guidance. https://www.dot.state.mn.us/stateaid/projectdelivery/pdp/tools/flexible-pavement-design-guidance.pdf (accessed by June 11, 2020)

68. Zhang K, Liu Y, Nassiri S, Li H, Englund K (2021) Performance evaluation of porous asphalt mixture enhanced with high dosages of cured carbon fiber composite materials. Constr Build Mater 274:122066

69. Zhang K, Lim J, Nassiri S, Alshareedah O, Li H, Englund K (2020) Field pilot study of porous asphalt pavement reinforced by cured carbon fibre composite materials (CCFCMs). Int J Pavement Eng. https://doi.org/10.1080/10298436.2020.1774765

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