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Porous asphalt concrete: A review of design, construction, performance and maintenance

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Abstract

Porous asphalt concrete (PAC) is an open-graded friction course that is specifically designed to have high air void contents for removing water from the pavement surface. PAC surfaces, which include open-graded friction courses, permeable friction courses, and drainage asphalt pavements, have increasingly gained acceptance among agencies and industry in the world. PAC might be susceptible to freeze-thaw damage in cold climates and require winter maintenance practices. The life span of PAC pavements shows a large variation depending on climates, traffic volumes and loadings, design and construction practices. The objective of this paper was to review design, construction, and performance that could maximize the advantages and minimize the disadvantages associated with the use of PAC mixtures. A consolidated review of the worldwide literature on PAC applications was conducted, with attention to the use of PAC in agency practices, and specifications for PAC from the world were evaluated. Based on an analysis of the results of this review, two key features were emphasized: (1) a recommended practice for material selection and design of PAC, and (2) a recommended practice for PAC construction and maintenance. Key points include a careful assessment of the PAC drainage and an adequate asphalt content to improve the performance of the pavement surface. A proper binder content stabilized by additives such as fibers and polymers is essential to ensure sufficient film thickness that is critical to the durability of the PAC mix in the long run.

Keywords: Open-graded friction course; Permeable friction course; Drainage asphalt pavement

1. Background

Porous asphalt concrete (PAC) is an open-grade material with interconnecting voids that allow water to flow freely the material to a binder course. Safety- and environment-related benefits to PAC mixes have been recognized for years [1-5]. The use of PAC mixes to remove water from the surface provides good contact between tires and the pavement surface, thus minimizing the potential for accidents and fatalities during rainy weather, and, at the same time, reducing traffic noise levels. Fig. 1 illustrates the difference in porosity between PAC and dense-graded asphalt concrete (DGAC). During a rainy day, there exists a thick water film on the DGAC surface, but no water film on the PAC surface. PAC allows water to flow through the surface layer because of high porosity as shown in Fig. 1. Because of these benefits, PAC surfaces have gradually gained acceptance around the world [5-9].

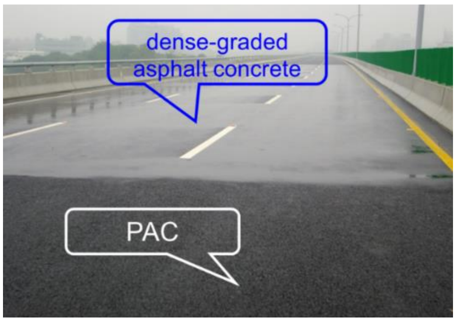

Fig. 1. Difference in water transport on PAC and dense-graded mixes.

Benefits related to improved safety also include reduced glare and improved visibility of pavement markings. In addition, benefits related to improved driver comfort include smooth pavements, increased confidence of drivers during rain events because of reduction in potential hydroplaning, reduced splash and spray, reduced glare, and reduced potential for permanent deformation [4-5,10]. Stone-on-stone contact and particle interlock of the coarse-aggregate fraction is one of the main characteristics of PAC mixtures that is essential to provide particle interlock and adequate resistance to permanent deformation.

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There is a wealth of studies that document the current design and construction practices of PAC mixes as well as their performance from laboratory and field perspectives. Evolution over last three decades including polymer-modified asphalt and other practices transforms the use of PAC mixes. However, the life span of PAC pavements shows a large variation depending on climates, traffic volumes and loadings, design concepts and construction practices. In order to further advance the current state-of-the-art PAC guidelines to meet regional, traffic, and climatic challenges, a comprehensive, critical review on the currently available applications of PAC mixes to pavement construction and maintenance is essential. Thus, the main purpose of this paper was to assemble and present the current knowledge about the benefits, design, construction, performance and maintenance of PAC pavements in comparison with those of conventional asphalt pavements.

1.1. History

Open-graded asphalt mixtures have been used since early 1940s [11]. Porous asphalt concrete (PAC), open-graded friction courses (OGFC), drainage asphalt pavements, or porous friction courses are special asphalt mixtures characterized by a large content of interconnected air voids [2,4,5,10-11]. In general, the air void content is at a minimum of 18 percent. Similar mixtures with voids contents as high as 25 percent are generally utilized in Europe and Asia. In comparison with dense-graded hot mix asphalt mixtures, the volumetric property of open-graded asphalt mixtures results in high permeability values and noise reduction capacity. These two properties are the primary advantages and reasons for selection of porous asphalt concrete [5,10,11-13].

In this paper, the mixture is designated as PAC to follow the original term cited in the sources. These interconnected voids make these mixtures highly permeable with the capacity to reduce tire-pavement noise [10,14-20]. PAC mixtures require a different mix design method and special construction as well as maintenance considerations. The differences in PAC and OGFC layers are listed in Table 1. An OGFC layer, relatively thin, has lower void percentages in the range of 10 to 15% by volume of total mix as compared with PAC. Permeable friction asphalt course, an alternative treatment to traditional OGFC mixtures, is typically designed to have 20% air voids. PAC layers are thicker, 3 to 5 cm instead of 1.5 to 2.5 cm. In addition, PAC mixtures have larger nominal maximum aggregate sizes to provide a better free-draining layer. PAC is distinguished from OGFC by differences in air voids, thickness and aggregate size [14-21]. Highway agencies require a specific thickness range for PAC mixes based upon weather condition, material availability and construction practice [22-24].

1.2. Benefits of porous asphalt concrete

Benefits related to PAC pavements include reduced splash/spray, improved wet weather frictional properties, reduced traffic noise, improved visibility of pavement markings, reduced glare, smooth riding layers, and resistance to permanent deformation. Depending on the required thickness, PAC pavements can also be economical because they can typically be placed in thinner lifts than dense-graded mixes [25-26]. Highway agencies have seen a decrease in wet pavement accidents on roadways with PAC mixes. A traffic safety study in Japan showed that PAC significantly reduced the number of fatalities during rainy weather when results were compared to standard dense-graded mix [27].

Table 1
Differences in PAC and OGFC layers [4-5,14-24].

Properties	PAC	OGFC
Thickness (cm)	3-5	1.5-2.5
Air voids (%)	15-25	10-15
Nominal maximum aggregate size (mm)	12.5, 19.0	9.5

1.2.1. Safety-related benefits

The risk of hydroplaning during a rain event is increased in low-lying areas, at the transition of super-elevated curves, or when rutting of a dense-graded mix has occurred. This surface water may cause a water film to form between the tire and the pavement, affecting the tire-pavement interface friction and the ability of drivers to control the vehicle. A PAC surface allows water to drain through the surface and exit onto the shoulder. This limits the risk of hydroplaning and increases the friction resistance. By limiting the amount of water that is standing or flowing across the pavement surface, users are provided a safer traveling experience during rain events [1-5,25]. The macro- and micro-texture of PAC pavements could enhance mean profile depth and dynamic friction as shown in Fig. 2. Macro-texture is defined by the shape, size, and overall particle arrangement while micro-texture refers to the texture of the aggregate particle surface and small sand-sized particles in the exposed asphalt mortar. Both macro- and micro-textures significantly affect the skid resistance; therefore, PAC pavements will improve frictional properties, especially during wet weather [10,15,18,27].

1.2.2. Environmental benefits

While some highway noise comes from the vehicles themselves, a large part of this noise comes from the pavement-tire interaction. Fig. 3 corresponds to the influence of a sound-absorbing porous pavement. A porous pavement can dissipate sound energy generated by contact between the tire and the surface. This is especially true when the highway speed is above 70 kph [28-35]. Metropolitan areas have the most need for noise reduction due to the close proximity of businesses and homes to the highway. The obvious reason for the need of noise reduction is the quality of life of the population. In general, PAC pavements reduce pavement-tire interaction noise above 1,000 Hz [36-39]; furthermore, a study shows that the noise absorption coefficient was sensitive to thickness [7,40-44].

Another environmental benefit that has recently been observed is the ability of PAC to act as a cool pavement to combat Urban

Fig. 2. Macro- and micro-texture of PAC mixes after approximately 8 years of service.

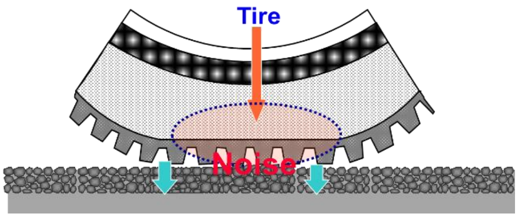

Fig. 3. Illustration of sound absorption of propagation over PAC.

Heat Islands (UHI) [34-35]. Urban heat islands are a temperature phenomenon that occurs in urban areas. Radiation from the sun is absorbed by rooftops, pavements, sidewalks, and buildings. Because of the close proximity of these types of structures within an urban area, the sun's energy can be reflected or radiated from the structures resulting in increased temperatures. Air temperatures within urban areas can be 27 to 50°C hotter on hot dry days than in nearby more rural areas [34-36]. "Cool pavements" are a strategy for reducing the UHI. Open-graded mixes, whether PACs or porous pavement parking lots, are technologies that are considered cool pavements [35-37].

2. Drainage and mix design

PAC pavements need to be designed to have interconnected air voids and adequate cross slope in the underlying layer during rainy days, and to drain the water away from the surface and off the roadway. At the same time, they still provide engineering properties, adequate friction and noise reduction achieved from the open-graded design of the pavement [4-5].

2.1. Drainage considerations

Drainage significantly affects the performance of PAC pavements. There is an old adage that the three most important factors in pavement performance are water, water and water. The drainage capacity of a PAC is a direct function of the air voids and gradient as shown in Fig. 4. The air void content plays an important role in achieving the water removal and noise reduction properties. Adequate aggregate gradation and proper asphalt content could provide optimum air voids. Water could migrate through the PAC and under traffic is forced into the underlying mixture. Stripping could occur in the layer directly underneath the PAC over a period of time. The underlying layer should be impervious so that water cannot infiltrate into the soil subgrade below. The underlying course needs to be tested for moisture susceptibility, and should contain an antistripping agent to ensure that stripping does not occur [4,9,45-46].

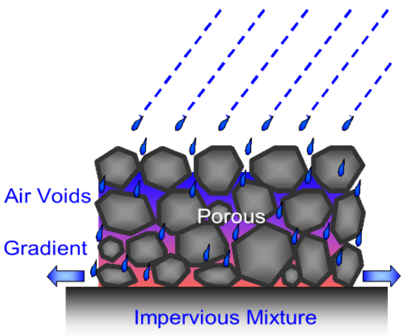

Fig. 4. Drainage considerations.

2.2. Basic concept for mix design

Porous asphalt mix design involves procedures developed to establish the properties of asphalt mixtures to withstand the effects of traffic and the environment during its service life. These procedures include determining aggregate properties and aggregate gradation, and selecting asphalt cement and binder content to be used for that gradation. There exist various degrees of variability among agency practices allowing for differences in the mix design for PAC pavements [13,47-52]. The focus of this review is to take an analytical approach to these differences and to help prevent distresses such as premature raveling and cracking. PAC mixes consist primarily of coarse aggregate, air voids, asphalt binder, and stabilizing additives as shown in Fig. 5. Aggregate mineralogy is not specified in most specifications because of limitations and availability of local resources. A small amount of fine aggregate and stabilizing additives help to maintain the stability and cohesiveness of PAC mixes [4,5,53-54].

2.3. Aggregate and gradation

Aggregates typically constitute about 95% by weight of PAC mix. They supply nearly all of pavement bearing capacity. Aggregate quality and physical properties are critical to the long-term performance of PAC mixtures, particularly to rutting resistance. Stone-on-stone contact is the vital backbone of PAC mixtures, and 100% crushed aggregate is required [10,13,51-52]. Another mix that relies heavily on a stone-on-stone skeleton to maximize rutting resistance is called stone mastic asphalt (SMA). SMA is a gap-graded asphalt mixture held together by high binder and filler contents. However, SMA mixtures are typically designed at 4% air voids like DGAC to ensure an impermeable pavement, which differentiates them from PAC mixtures that are permeable [55-56].

The requirements of aggregate property for agencies are listed in Table 2. The LA abrasion value and shape of coarse aggregate in PAC are much more important than those in conventional dense-graded mixtures. Flat and elongated proportions should be closely controlled to provide a high interlocking mechanism for PAC mixes [4,57-62]. The LA abrasion relates to the resistance of aggregate to polishing and potential loss in the frictional chracteristics. The maximum recommended LA abrasion for PAC mixes is required to be less than 30 [13,52,57].

The aggregate gradation for PAC provides for a significant amount of air voids in the mineral aggregate. The air voids in the PAC are typically designed to be approximately 20%. Better durability and less clogging has been noted in the mixes having more than 20% air voids [53]. After suitable aggregate sources

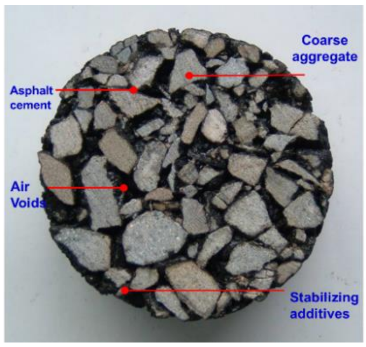

Fig. 5. Key elements of PAC mix design.

Table 2
Aggregate specifications for PAC mix designs [13,52-62].

Properties		AASTHO	ASTM	Japan	Taiwan
Coarse Aggregate					
Flat & elongated (%)	3:1	-	-	≤12	≤10
	5:1	≤5	≤10	≤5	≤5
Soundness (sodium sulfate, %)		≤10	-	≤12	≤12
Specific gravity (SSD)		-	-	≥2.45	≥2.45
Absorption (%)		-	-	≤3	≤2
LA abrasion (%)		≤30	≤30	≤30	≤30
Fracture face (%)	one	-	-	100	100
	two	-	-	≥95	≥90
Fine Aggregate					
Soundness (sodium sulfate, %)		≤10	-	-	≤15
Sand equivalency (%)		≥50	≥45	≥50	≥45

Note: "-" = not applicable

have been chosen, the optimization of the mix can begin by creating three trial blends that fall on the coarse limit, fine limit, and in the middle of the recommended gradation range. The majority of the gradation requirements are for mixes whose maximum aggregate size is 9.5 mm and 12.5 mm [5,60,63-78]. Netherlands and Taiwan have a mix design whose maximum aggregate size exceeded 12.5 mm for PAC. Filler contents vary depending on the maximum aggregate size of the design. Agencies allow anywhere from 0% to 7% passing the 0.075 mm sieve (P-200) in PAC mix designs. Experimental results indicate that the P-200 content of PAC mixes could be optimized between 4% and 6% to enhance durability [5]. Highway agencies use both hydrated lime and Portland cement as a filler. These two types of mineral fillers double up as an antistrip agent to prevent moisture damage to the PAC mix, and their dosage ranges from 1% to 3% by weight of total mix [4,21,53,63].

2.4. Asphalt cement

An increasing number of heavy trucks and axle loads take their toll in asphalt pavements. In addition, the bitumen inside PAC mixes is exposed to oxygen in the atmosphere and is likely to subject to oxidation and consequent embrittlement. The use of modified binders becomes prevalent after studies showed that modifying the binder could increase the life of the pavement and prevent draindown of a PAC mix [3,5,64].

Britain used both modified and unmodified binders but required a 100-penetration value [16]. The Netherlands and Switzerland do not require modified binders, but Switzerland allows modified binders as an alternative to conventional binder. Highway agencies in the U.S. and Asia primarily use polymer modification, SBS specifically, while South Africa uses both polymer and rubber in their PAC mixes [5,19,64-65]. Binder modified with SBS may provide better cracking resistance than GTR for PAC mixes [65-66]. Asphalt cement holding aggregate particles in position in PAC is essential to provide good resistance to weathering, and its content as well as properties are critical to the durability of PAC mixes [22,28-29].

2.5. Stabilizing additives

Stabilizing additives come in several forms including fibers, fillers and polymers. Fibers are most commonly used to provide stability to the mix and to prevent draindown of the binder. Draindown is an issue for a PAC mix because of its open-graded gradation in nature. The aggregate blend has little material passing the 4.75 mm sieve and a relatively low amount of P-200 material compared to dense-graded mixes. This results in a much lower aggregate surface area for PAC mixes, allowing for a thick coating film of asphalt binder on the aggregate particles. A typical film thickness of a dense-graded mix is approximately 8 microns, while a porous mix is typically around 12–30 microns [5]. The combination of polymer-modified binders and fibers could help prevent draindown as well as reinforce the film thickness of the asphalt binder. Stabilizing additives such as cellulose or mineral fibers are typically used in PAC mixtures to prevent draindown during production, storage, transportation, placement, and hot summer weather [63-67]. Cellulose fibers have an irregular ribbon shape, and to hold more binder than straight-shaped mineral fibers. Because of these differences, the dosage for cellulose and mineral fibers is typically 0.3% and 0.4% of the mix mass, respectively [68-71].

2.6. Binder content

Since PAC mixes are different from dense-graded mixes, the asphalt content cannot be selected based on a specified air void level. Trial asphalt contents, normally in 0.5% increments, are fabricated and then the engineering properties of the PAC mix are considered. The properties for PAC mix design can be found in Table 3. Design specimens are to be compacted using 50 blows per face of a Marshall hammer, or a gyratory compactor to a design level of 50 gyrations [51-54].

Table 3
Mix properties for PAC mix designs [13,51-54,72].

Mix properties	AASTHO	ASTM	New Zealand	Japan	Taiwan
Air voids (%)	18-22	≥18	20-23	≥18	15-25
Blows or gyrations	50	50	50	50	50
Abrasion loss (%)	≤15	≤20	≤15	≤20	≤20
Tensile strength ratio	≥0.7	≥0.8	≥0.8	≥0.7	≥0.8
Draindown (%)	≤0.3	≤0.3	≤0.3	≤0.3	≤0.3

Note: "-" = not applicable

Voids in the coarse aggregate (VCA) were considered in PAC practices. The compacted mix VCA values (VCA_{mix}) was required to be less than the dry rodded coarse aggregate VCA (VCA_{DRC}) so that the aggregate skeleton has stone-on-stone contact. A recent NCHRP report suggests that VCA may not be applicable for PAC mixes since they are typically placed in relatively thin thickness [5].

The service life of PAC pavements is limited by low asphalt content (i.e., dry mix) and binder aging, and is evidenced by increased levels of raveling of the surface [3,70,72]. A combination of draindown and abrasion loss tests are considered for selecting the optimum asphalt binder content as shown in Fig. 6. The Cantabro stone loss procedure has shown to be a good indicator of resistance to raveling [5,17,23,73]. The Cantabro abrasion loss is suggested to identify a minimum asphalt binder content. Typical asphalt contents range from 5.0% to 7.0% by weight of the total mixture depending on the nominal maximum aggregate size and the aggregate gradation [4,74]. As the asphalt content increases, the durability of the PAC mixture improves; but the risk of draindown also increases.

A maximum asphalt binder content is identified by conducting a basket drainage test. An increase in asphalt binder improves durability, but too much asphalt binder leads to draindown. This allows the designer to select the optimum based on an adequate range of binder contents. The total asphalt content for a PAC mix is typically higher than that for a dense-graded asphalt mix with the same nominal maximum aggregate size. A relatively high binder content is needed to ensure adequate film thickness that is essential to the success of asphalt mixes [4,12,38,48,70,75].

Raveling is mostly influenced by the binder content in the mixture and its total air void content. The optimum binder content should be selected based upon the concept of minimizing draindown potential and, at the same time, maximizing durability. A recent study in Florida indicates that an increase in asphalt content by 0.6% significantly enhances the service life of PAC pavements [76]. While durability and draindown potential are utilized to define the range of allowable binder contents, a fixed binder content of 4.5 to 5.5 is utilized for PAC pavements in the Netherlands [20]. Furthermore, the PAC mix must meet certain criteria when tested using a wheel-tracking device, semicircular bending test, and indirect tensile strength [5,77-81].

The most widely used type of performance testing conducted during PAC mix designs is moisture sensitivity. Conducting moisture susceptibility testing on PACs is primarily to use indirect tensile strength testing and tensile strength ratios (TSR) according to AASHTO T 283. The second moisture susceptibility test is the boil test based on ASTM D3625 [4,5,73]. Other tests also have been specified in Europe. Moisture conditioning of Cantabro Abrasion loss samples are tested to determine if any stripping of the aggregate has occurred [74].

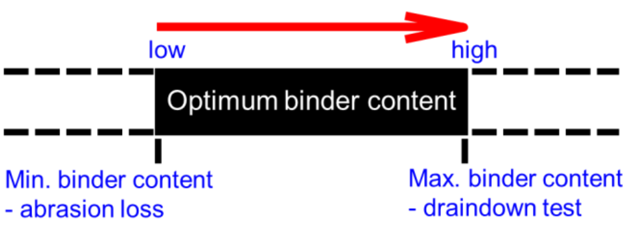

Fig. 6. Determination of optimum binder content for PAC mix designs.

2.7. *Summary of mix design*

Table 4 presents a summary of current practices on PAC mix design in the U.S., Europe and Asia. In the U.S. these types of mixtures are known as open-graded. In Europe and Asia, these materials are known as porous asphalt and porous asphalt mixes, respectively. They are used for the same reasons as in the U.S., as well as to improve permeability and, consequently, wet-weather friction, which is related to the frequency of traffic accidents.

All mix criteria include a minimum air void content of 18 percent of more. In general, porous mixes used in Europe and Asia have higher air void contents than those in the U.S. The air voids in the porous asphalt mixes range between 20 and 25 percent; the open-graded mixes in the U.S. generally have air void contents of less than 20 percent. European and Asian countries tend to use larger nominal maximum aggregate size specifications, while there is tendency to use smaller NMAS specifications in the U.S. The drainage capacity of a PAC mix is a direct function of the air voids. In most of the cases, highway agencies tend to increase the nominal maximum aggregate size from 9.5 mm to 12.5 mm and 19mm to obtain sufficient interconnected air voids for the drainage path. In Europe and Asia, the tensile strength ratio (TSR) for porous mixes is specified as at least 80 percent; in the U.S., the required value is usually above 80 percent for those states that have a tensile strength ratio specification.

3. Construction

3.1. *Production*

Properly designed, produced and constructed PAC is durable and exhibit service lives up to 18 years [4,10,15,19,25-26]. Production of PAC mixes is similar to typical dense-graded asphalt mixtures with modification when required. The primary modification required at the production facility is the addition of a fiber-feeding device. Depending upon the type of plant, a method to incorporate fibers into the production process can differ. The fibers are usually introduced either loose or in pelletized form. In the case of batch plants, the fiber is added at the pugmill. Bales of loose fibers have been added manually into the pugmill and also the fibers have been blown into the pugmill from a fluffing device. Pelletized fibers can also be placed directly into the pugmill either manually or from a feeder. Within drum plants, fibers are generally blown continuously into the drum. The fiber line is generally placed upstream of the asphalt binder line. This is done so that the fibers are captured by the asphalt binder and do not end up in the dust collection system [4,16,18,26].

Mixing time in the plant needs to increase to ensure that the fibers are homogenously dispersed within the PAC mix. In a batch plant, the dry mixing time may also be increased to ensure that the stabilizing additives are sufficiently distributed in the mix. Care must be taken on the screen decks of batch plants. PAC gradations

Table 4
Summary of current practices on PAC mix design [4-5,14,81-84].

Items	U.S.	Europe	Asia
Materials	Open-graded	Porous asphalt	Porous asphalt mixes
Air voids (%)	< 20	20-25	20-25
NMAS (mm)	9.5, 12.5, 19	12.5	12.5, 19
TSR (%)	≥ 80	≥ 80	≥ 80

consist of a large percentage of single size aggregates; therefore, override of the screen decks and hot bins can occur [5,14,22].

A maximum and/or minimum temperature for mixing in the plant is required based upon asphalt binder type and grade. PAC mixtures using conventional asphalt binder should be produced at a temperature approximately 10°C lower than for conventional dense-graded mix. This reduces draindown of the asphalt component. This reduction in mixing temperature might not be required with polymer/rubber-modified asphalt mixtures because of their inherently higher viscosity [21,58,85].

Silo storage time is specified for PAC mixtures to minimize the potential for draindown. The time limit allowed PAC to be kept in a silo should be kept to a shorter time depending upon mixing temperature and binder content. The storage time for the PAC mix held typically is no more than 2 hours [3-4,68].

3.2. Transportation

Haul distances should be limited to keep the workability of the PAC mix and the ability to compact the mix after it has been placed by the paver [69,72,74]. Both of these factors are highly dependent on the temperature of the mix. Some highway agencies set their limit in the range of 80 to 120 kilometers with a minimum mixture temperature requirement. Others limit the haul distance by time no more than 1 or 2 hours [4,22,86].

Agencies and industry require that the mix be protected from cooling during transportation. Tarps should be used to minimize the amount of cooling that takes place during transportation. Material transfer vehicles that remix the PAC before being deposited into the paver are desirable. In addition, a minimum mix temperature needs to be specified when the truck reaches the paving site. This minimum temperature varies from agency to agency depending on climate zone and binder type. A minimum temperature should be more than 120°C, and the temperature could be as high as 150°C [5,12,16]. Other agencies set the minimum temperature at 10 to 20°C below the mixing temperature or the target compaction temperature [13,57]. Release agents have to be non-petroleum, and diesel fuel should not be used for the truck bed. [4,26].

3.3. Paving operation

A tack coat is used to ensure a sufficient bond between the existing pavement surface and the PAC mix. The use of tack coat varies among agencies and industry. The types of tack coat used include different types of emulsions such as RS-1, CRS-1, SS-1, and CSS-1. The application rate ranged from a low of 0.18 l/m^2 to an amount as high as 0.90 l/m^2 [14,87-88]. The tack coat should be sprayed using a pressure distributor to apply a uniform application of the material to the road surface [22,26,88].

Distresses might result from issue with placing PAC during cold temperatures. An ambient air temperature needs to be specified for placing PAC, although the minimum temperature varies from agency to agency. The minimum air temperature required is from 10°C to as high as 20°C [16,80,87]. Other agencies in cold climate zone specify a minimum base temperature required to reduce the rate of cooling of the mix and increase the time available for compaction. The minimum base temperature is also dependent on the type binder used in the PAC. Asphalt cement with a higher grade (i.e., PG 58S-28 versus PG 64E-22) requires a higher minimum temperature [5,89].

Laydown of porous asphalt mixes is no more difficult than for dense-graded materials. The preferred method for compacting PAC mixes in Europe includes the use of a 10- to 12-ton steel-wheel roller, while 8- to 9-ton tandem rollers are appropriate to complete the compaction process on thin layers [4,5]. Typically, 2 to 4 passes of a breakdown roller and 1 to 2 rolls of a finish roller are sufficient to compact PAC layers. The goal of compaction is to seat the aggregates instead of achieving a certain density. Keeping a maximum distance of 15 m between the roller and the paver is recommended. [5,16,89].

Heavy rollers should be avoided as they can lead to excessive breakdown of the aggregates. Static steel-wheel rollers are the recommended equipment for compacting PAC mixtures. Vibrator rollers are not recommended because of the potential for fracturing the aggregate within the mix. Pneumatic tire rollers are generally not used because kneading action reduces the mixture drainage capacity by closing surface pores. In addition, pneumatic tire rollers tend to pick up mix during compaction. Handwork is difficult because of the lack of fines and rapid cooling due to the open-graded mix [5,16,86-90]. Permeability measurements were made on porous friction courses using STM C1701 and the National Center for Asphalt Technology (NCAT) methods. Permeability measured by ASTM and NCAT methods were correlated with values ranging from 0.03 to 0.2 cm/s depending on air voids [74].

3.4. Summary of construction practices

A summary of the best current practices for PAC construction around the world is presented in Table 5. Production of PAC is similar to the production of conventional hot-mix asphalt mixtures. In the U.S., most of PAC mixtures are produced in a drum mix plant, and they are primarily mixed in the pugmill of a batch plant in Europe and Asia. All the feed systems of the plant need to be carefully calibrated prior to production of PAC. Operation of the aggregate cold feeds can have a significant influence on the PAC mixture. Whether in the drum or the pugmill, fiber pellets are mixed with the heated aggregate and the heat from the aggregates causes the binding agent in the pellets to become fluid. This allows the fiber to mix with the aggregate.

Transportation of the PAC mix to the construction site is conducted using the same trucks for dense-graded mixes. Highway agencies have limited haul distance to 120 km or haul time to no more than 1 hour. These limits are to deliver the PAC mix to the project site at the appropriate temperature. The paving process of PAC is similar to the placement of conventional dense-graded mixes. Typical asphalt pavers are utilized. A high auger speed may have a tendency to shear the mortar from the coarse aggregate thus causing fat spots in the pavement. The paver wings should not be lifted except when the material is to be discarded. Static steel wheel rollers are used for compacting PAC layers. Rollers should be 12 tons or smaller to prevent excessive aggregate breakdown. To achieve correct compaction on the PAC mat, the roller should follow close behind the paver for the temperature to be sufficient.

4. Performance

Open-graded asphalt mixtures have been used around the world for more than 80 years; however, performance has been mixed [5]. Depending on climates, traffic volumes and loadings, materials and construction practices, the service life of PAC pavements

Table 5
Summary of current practices on PAC construction [4,10,18,22-26,29,57-58,66-75,89-90].

Items	U.S.	Europe	Asia
Production	Drum plant	Batch plant	Batch plant
Transportation	<120 km, <1 hr	<120 km, <1 hr	<120 km, <1 hr
Paving	Typical paver	Typical paver	Typical paver
Compaction	Static steel roller	Static steel roller	Static steel roller

shows a large variation. The life span of PAC pavements has been reported from 8 to 18 years, somewhat less than typical dense-graded mixtures [3-5,21-23,53-54,64,91-93]. In the Netherlands, over 80% of the roadways are paved with PAC pavements. Although the Netherlands has adequately designed mixes with good success, the design life of PAC pavements exhibits a wide range of 5 to 18 years. Highway agencies in the Netherlands have a standard maintenance practice of rehabilitating 5% to 7% of their PAC pavements annually [20-23,80].

The lack of PAC use in cold climates seems to be primarily due to water freezing in the pavement that could lead to premature failures and safety concerns. Having an open texture means that PAC pavements are accessible to water and likely to degrade if there are frequent freeze/thaw weather cycles. Unsatisfactory experience is associated mostly with the length of service life and the failure mechanism at the end of service life. At the end of life, the pavement begins to ravel and deteriorated rapidly, often in a matter of months. A short life might make agencies and industry less likely to use porous asphalt surfaces in cold weather [10,17,20,23].

4.1. Construction-associated distresses

Raveling is a major issue associated with the construction of PAC mixes. The following factors could lead to issues with PAC pavements during production and paving operation: (1) mix properties, (2) mixing temperature, (3) asphalt content, (4) tack coat, and (5) compaction temperature [11,22,25]. Inconsistent mix properties and temperatures during production could lead to raveling. Mix temperature is one of the biggest concerns when producing PAC mixtures. When raveling is linked to the high mix temperature, it is also a durability issue that begins at the top of the pavement. Binder aging could be severe at the top part of the pavement, because asphalt cement is in contact with the ambient air and the pavement temperature is higher [5,14,94-97].

Consistent mix temperatures and short haul times are critical for adequate placement. If a contractor follows quality control plan, visibly defective workmanship or materials may be identified. In-situ inspector should be in communication with the contractor as soon as visibly defective PAC mixes are observed. An appropriate action to remedy will depend on the construction situation itself and agencies policies practices [97-99].

4.2. Raveling

PAC pavements primarily fail by raveling, and this type of distress can be classified as short-term or long-term raveling. Short-term raveling is caused by intense shearing forces between tires and pavement interface that occurs within newly placed PAC mixes [71,76]. The draindown and mixture temperature problems led to raveling. Areas without a sufficient amount of asphalt binder are prone to raveling, while areas dry in asphalt binder could not provide the desired engineering properties [100-101]. Placing the mix at an inadequate temperature, or not properly compacting the mix could fail to maintain the structural integrity of the pavement [78,99]. Other construction issues such as waiting on trucks or long-haul distances can also play a part in short-term raveling. If construction is on hold while waiting on trucks, it can cause differences in the temperature profile of the pavement, resulting in cold areas. Likewise, if a cold mix is placed on joints or transition areas, it will not attain adequate compaction due to lack of heat [5,72,94].

Long-term raveling is the primary reason for the termination of PAC pavements. PAC mixtures would deteriorate slowly for the first 5 to 10 years, and raveling, if it happens, might significantly increase after this point [17,23,98,102] In the long run, a reduction in asphalt content and binder creep (i.e., long-term draindown) may be the reason for raveling [15,100]. Thinner film at the surface could accelerate aging at the surface and raveling potential. In addition, PAC mixtures should avoid being placed on areas such as ramps where vehicles may stop, accelerate, and make turns. These maneuvers exert extra force on PAC pavements that could lead to dislodge aggregates from open-graded mixes. Raveling occurs when tires dislodge aggregate particles from pavement surface downward [5,79].

4.3. Delamination

Delamination occurs when the bond between the underlying surface and the PAC is inadequate and causes a slip surface. Delamination of PAC pavements is due largely to construction practices and tack rate [86,88,90,103]. When a PAC mix is placed over a dense-graded mix, a heavier tack coat should be placed so that an adequate bond can be formed. Since there is less contact area for PAC mixes, a heavier tack coat is needed to compensate than for dense-graded mixes. A tack emulsion is applied with a spray paver at a spray rate of 0.18 to 0.90 l/m^2 [4]. If the underlying layer has air voids of more than 5%, it is deemed permeable [104]. A slow-setting emulsion should be placed at a rate of 0.22 to 0.45 l/m^2 residual asphalt in order to seal the layer [3-5,14]. Delamination can also be caused by moisture damage and may occur due to the mix being cold when placed on the receiving surface [9,27,34,70].

4.4. Cracking

Cracking of PAC mixes is not as visible as raveling, but it could occur. The pavement design in the Netherlands entails designing to prevent classical bottom-up fatigue cracking [21,105]. Top-down cracking could happen due to the shear stress applied to the pavement by tires [22,54,106]. Because of the relatively rigid tire wall and the structure of bias ply tires, the ribs of the tire cause an inward shear stress at the surface of the pavement by pulling the ribs into the center of the tire. The type of bond material at the interface between the PAC and underlying layer is critical in mitigating top-down cracking [54,101]. When porous asphalt mixtures are used above pavement structures containing cement-treated road bases, an additional layer of dense-graded asphalt mixtures is provided to assist in preventing reflective cracking. Reflective cracking that appears in a PAC will provide an avenue for water to penetrate into the pavement structure, thereby, increasing the potential for pavement deterioration [53,90].

4.5. Loss of noise reduction over time

One of the primary reasons for the loss of noise reduction is condensation and clogging of the pores in PAC pavements. A study was conducted to measure the noise levels of various PAC mixtures in different traffic loading areas and compared those to the air voids of the pavement [101]. The air void range of the pavements was reduced from 20% to 14% within a service life of 8 years, which correlated to an 8 dB (A) range in noise results. As air void content decreases, the noise level increases. This seems to indicate that if the PAC becomes condensed and clogged and the air void content decreases, there will be an increase in the noise level. Studies conducted to investigate the noise levels of seven different PAC mixes also presented similar results [40-42,97].

5. Maintenance

General maintenance of PAC layers is similar to that of dense-graded asphalt pavements. Rutting, cracking, skid resistance, smoothness, and raveling need to be monitored. Minor rehabilitation entails small local repairs necessary because of small damage or distress with the rest of the pavement layer in good condition. Local distresses can be repaired by replacing the area with dense-graded mix. A discontinuity in the drainage path will occur, and the discontinuity may not be considered severe when dealing with small localized areas [2-4,26,49,107].

5.1. Condensation and clogging

PAC pavements are inevitably condensed by traffic loading and clogged with dust, silt, and other debris over time [1-5,22-23,53-54,70,101]. During the service life of a porous asphalt layer, dirt and debris are likely to clog the layer. Clogging decreases the ability to drain water through the PAC layer. Common methods for de-clogging porous asphalt layers include the use of highly pressurized water or the use of a suck-sweep cleaning truck [2,107]. The cleaning of PAC layers that have become filled with debris could be very difficult. High pressure water with subsequent vacuuming can clean porous pavements; however, this technique may not be very successful in restoring permeability. The process of vacuum sweeping requires a large maintenance cost and can potentially damage the pavement [3-5,14]. In addition, cleaning PAC mixtures will not be effective when reduction in air voids results from traffic compaction [19]. If cleaning techniques start while the layer is still permeable, instead of clogged, favorable results should be to maintain permeability for a longer period of time [3]. Furthermore, fog seals have used as a preventative maintenance treatment [3-4].

5.2. Winter maintenance

The role of winter maintenance is to clear roads from ice and snow at an acceptable cost, so that drivers can use the major roads almost normally under all but exceptional winter conditions. The surface temperature of porous asphalt layers are generally lower than that of dense-graded layers. This condition could result in a thin layer of ice on the pavement surface due to condensation and near freezing temperatures. Traditional winter maintenance methods include salting, sanding, de-icing chemicals, and snow plowing. Salting can be used, but needs to be done carefully. At lower temperatures, preventative salt spreading is not as effective. An increased frequency is often needed. Deicing chemicals can be used, but they need to be applied more often as the chemicals will drain through the pavement structure. Sanding operations should be avoided as they tend to clog the pavement pores [10,22,32,70,85,108].

5.3. Rehabilitation

Major rehabilitation is conducted when the entire PAC layer is in need of repair. The maintenance activities generally consist of milling the existing layer and replacing with a new wearing layer. Direct placement of new dense-graded over porous mixture is not recommended because life of the new layer can be diminished by water accumulation inside the PAC [3,2,14,85]. The maintenance practice in New Zealand comprises the sealing of the existing surface by the application of bitumen tack coat followed by a layer of chip seal. The purpose of this layer is to seal off the voids in the existing surface prior to overlaying it with a porous asphalt layer. This membrane seal is applied immediately prior to the PAC overlay [72,89-90].

5.4. Summary of maintenance practices

Table 6 provides a summary of useful maintenance practices for PAC used in the U.S., Europe and Asia. PAC may become partially clogged due to dirt and debris deposited into the voids of the pavement structure over time. Three possible methods for cleaning a PAC pavement are with a fire hose, a high pressure cleaner, or a specially engineered cleaning vehicle. As a preventative maintenance, highway agencies could use a fog seal or a seal coat to rejuvenate a PAC pavement to halt light raveling or repair distressed areas. Chip seals may also be used to seal the surface of PAC when water damage to underlying layers is a problem.

There is a wide range of winter maintenance practices about winter maintenance for PAC because snow and ice accumulates differently on PAC pavements than on traditional pavements. Current winter maintenance methods include salting, sanding, de-icing chemicals, and snow plowing. Salting can be used, but needs to be done carefully. Small Salting pieces should be used to dissolve quickly and minimize pore clogging. Snow plowing needs to be done carefully as a PAC surface has less resistance to the blade of the snow plow. Rehabilitation is the solution if the severity of raveling or cracking becomes excessive. Most agencies will remove the PAC by milling it off and replacing it with another PAC layer.

Table 6
Summary of current practices on PAC maintenance [3-4,10,14,22,26,32,68,85,89,90].

Items	U.S.	Europe	Asia
Clogging	Fire hose	Cleaning vehicle	Cleaning vehicle
Preventative	Fog or chip seal	Fog seal	Fog or chip seal
Winter	Salting/plowing	Salting/plowing	Salting/plowing
Rehabilitation	Milling/replacing	Milling/replacing	Milling/replacing

6. Conclusions and recommendations

Advances and challenges in the use of porous asphalt concrete (PAC) for pavement construction and maintenance are reviewed and analyzed in this paper. Careful consideration of design and construction techniques is critical to ensure the success of the PAC mix. Based on information obtained through the literature review, the following conclusions and recommendations are drawn:

1. Benefits related to PAC pavements include reduced splash/spray, and improved wet weather frictional properties.
2. Sufficient lateral and longitudinal grade in the underlying layer are necessary to ensure adequate water discharge from the PAC mix.
3. Placement of PAC over an impermeable layer is required to prevent problems in underlying layers.
4. Flat and elongated proportions of aggregate should be closely monitored to provide a high interlocking mechanism for the PAC mix.
5. Both hydrated lime and Portland cement can be used as an antistrip agent to prevent moisture damage to the PAC mix.
6. The optimum binder content can be selected based upon draindown potential to improve durability. This relatively high binder content is needed to improve the resistance of the PAC mix to raveling.
7. Incorporation of fibers and proper use of polymer-modified binders in the PAC mix can allow the use of higher air voids (for drainage, and hence prevent stripping in the underlying layer), higher asphalt binder content (for durability, and hence prevent raveling) by controlling draindown, as well as to provide improved adhesion and greater resistance to aging of binder.
8. Mixing time in the asphalt plant needs to increase to ensure that the fibers are homogenously dispersed within the PAC mix.
9. Since PAC mixtures are characterized by draindown susceptibility, control of mixing temperature requires particular attention.
10. Limits on mixture storage and transportation times should be required because PAC mixes are prone to draindown.
11. Compaction of PAC mixtures is typically performed using static steel-wheel rollers.
12. Pneumatic-tired rollers are not used for PAC compaction because their kneading action reduces the mixture drainage capacity by closing surface pores.
13. Although cleaning of PAC in most countries is not common, maintenance practices may include occasional vacuum sweeping to ensure the longevity of the porous surface with repairs completed to address any localized deficiencies.

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