A review of using porous asphalt pavement as an alternative to conventional pavement in stormwater treatment

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Abstract
Purpose – Porous asphalt has been used for than 50 years, but it was originally developed in 1970 at Franklin institute in Philadelphia, Pennsylvania. By 1974 the first formalized procedure was created by the federal highway administration to design mixtures. Many researches on porous asphalt mixture have been conducted for the past two decades. However, there remains some concern about the potential adverse impacts of infiltrated surface water on the underlying groundwater. The purpose of this paper is to presents a short review on the application of porous asphalt pavement stormwater treatment.
Design/methodology/approach – In this paper, a critical review on history and benefits is presented followed by review of general studies of using porous asphalt pavement, and some recent scientific studies that examine potential contamination of soil and groundwater because of infiltration systems.
Findings – This paper indicates that porous asphalt pavement is more efficient than conventional pavements in terms of retaining pollutants, improving the quality of water and runoff while maintaining infiltration.
Originality/value – This paper may also help reduce land consumption by reducing the need for traditional storm-water management structures. However, on the other hand, the priority objectives which is minimizing increased flooding and pollution risks while increasing performance efficiency and enhancing local environmental quality-of-life is achieved.

Keywords Groundwater, Permeability, Storm water, Pollutants, Porous asphalt pavement

Paper type Literature review

Introduction

Storm-water management has become a critical issue. Communities all over the world recognize that managing urban storm-water is challenging. But most of the cities of the developed world rely on traditional systems (pipe and drainage network systems), which were developed in the nineteenth century. Traditional systems capture storm runoff and subsequently distribute it to nearby drainage systems. However, with fast urbanization, some of these systems have become inadequate, expensive and ineffective and inefficient. As a result of that, water quality issues, including oil, heavy metal and salt contamination, increase in intensity of rainfall and quantity issues, in turn increase. Also, when existing storm-water systems are overtaxed, a major health risk is caused by uncontrolled flood water mixing with sewage. Instead of focusing on traditional systems, sustainable urban drainage system (SUDS) challenges the traditional approach of wastewater treatment by optimizing the resource utilization and development of novel and more productive technologies. Many water management systems, which come under the generic title of SUDS, are difficult to retrofit and implement on a large scale because of space and cost constraints. This increase in the development and urbanization, natural ground pervious surfaces have been replaced with impervious surfaces, such as pavements. This could reduce the porosity of

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the natural ground surface and increase the amount of storm-water runoff, sediment transportation, erosion, hydroplaning and pollutant (Zachary Bean *et al.*, 2007). Permeable pavement systems have become a popular solution worldwide. Porous asphalt can be used in SUDS as a surface for a permeable pavement system (PPS) through which the amount of storm-water runoff, sediments transportation, hydroplaning, spray and pollutant transportation are reduced because of the void or porosity of the porous asphalt which allowed the water penetration through the pavement surface and then to the natural or underlying soil (Brattebo and Booth, 2003; Carlson *et al.*, 2014; Mullaney *et al.*, 2012; Putman and Kline, 2012).

Porous asphalt is designed to reduce the amount of water runoff by allowing the water to penetrate into the ground, instead of diverting the flow towards storm-water drains. This is achieved by screening or reducing the amount of fine aggregate and increasing the amount of coarse aggregate, placed on a bed of uniformly graded, clean washed aggregate with 40 per cent interconnecting air voids (Adams and Cahill, 2003). The high air voids content creates permeability that decreases the amount of storm-water runoff on the pavement surface, which in turn reduces the amount of splashing and spraying in wet weather, as a result of that the potential of hydroplaning is decreased and visibility is increased, both of which improved the safety of the roadways by reducing the number of accidents (Putman and Kline, 2012).

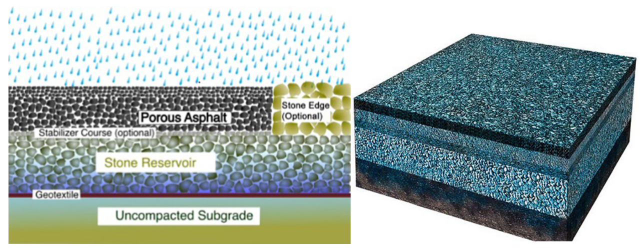
Also, the collection of research indicates that porous pavements are more efficient than conventional materials at degrading or retaining pollutants, improving the quality of runoff while maintaining infiltration. Total solids and metals were generally retained in upper soil layers receiving runoff or were filtered by porous pavements. Attenuation of hydrocarbons was also noted, particularly when filtered through sediment with high microbial activity. Also, the presence of its thick bitumen membrane and surface texture also helps increase friction and skid resistance, as well as the decrease in noise between the tire and pavement interaction, noise pollution along the road. It is clear that porous pavement can reduce human's noise annoyance by changing sound spectrum, especially for high-speed vehicles (Brattebo and Booth, 2003; Gilbert and Clausen, 2006; Jiang *et al.*, 2007).

Porous asphalt

Porous asphalt was originally developed at Franklin institute Philadelphia, Pennsylvania and tested throughout the 1980s although the idea of porous asphalt has been into existence since as early as 1944 as trail construction by Californian Department of Highway. Californian Department of Highway has been using chip seal to prevent entrance of moisture and air into the pavement and to increase the skid resistance on their highway networks, but then the performance has been unsatisfactory, particularly under high traffic, which made the department to go for plant mix seal coat which has the same benefit as chip seal and, at the same time, improves the performance of the chip seal.

Porous asphalt mixture is a thin permeable surface layer ranging from 19 to 50 mm, designed to allow water to penetrate through voids, thus improving surface friction more especially in wet weather (Figure 1). Porous asphalt mix has a

Figure 1 Typical cross-section of porous asphalt under construction



higher concentration of coarse aggregate than fine aggregates as in conventional pavement. This course consist of little sand or dust, with air void percentage of around 16-25 per cent as compared to the conventional pavement which has 2-3 percentage of air void. The 50/100 penetration grade of asphalt is used in this concrete depending on the surrounding temperature and viscosity characteristics desired. The mixture has high permeability, coarse texture and interconnected air void content throughout. These characteristics are achieved by using limited fines and high coarse aggregate and asphalt binder. Sometimes additives are also added (Mansour and Putman, 2012). The ability of the pavement to resist and carry heavy load without undergoing permanent deformation is because of this stone on stone skeleton. It carries the load and hold together in one place by the binder. The air voids plus its stone on stone skeleton gives this type of mixture many attributes. The porous nature of the porous asphalt mixture allows immediate penetration of water from the pavement surface. The texture of the large aggregates without fines provide better traction and also the void absorb sound energy as tire roll over the pavement in which the surface noise is reduced (Wurst and Putman, 2012).

Porous asphalt was developed to improve safety on roadways, but it also has many other advantages. The presence of interconnected air void content creates permeability that reduces the amount of water on the roadway. The water drains through the porous asphalt and into the stone bed, then, slowly, infiltrates into the soil. Many contaminants are removed as the storm-water passes through the porous asphalt, stone recharge bed and soils through filtration and microbial action. This reduces spray and splash in wet weather, thus reducing, hydroplaning and increase visibility. Also, friction and skid resistance are increased with the help of surface texture; also, noise between the tire-pavement interactions is reduced. Porous asphalt mixture offer better performing, driver friendly pavement, but at 30 to 40 per cent premium over conventional asphalt mixture. Also, porous asphalt mixture is lighter in weight than conventional pavements. A ton of material is able to cover more square yards of pavement surface area. Unfortunately, some disadvantages of porous asphalt mixtures have also been reported. The high air void content leads to an increased potential for raveling and accelerated aging, because oxygen has access to a higher surface area of the mixture (Kandhal and Mallick, 1998; Marsalek and Chocat, 2002). Porous asphalt is perhaps unique because it combines vehicular functionality with storm-water treatment and control. In addition, correctly designed and installed, porous asphalt has excellent potential for small- and larger-scale urban settings because of the value of vehicular functionality and the likely high "transferability" of the technology among practitioners (Drake *et al.*, 2014).

Description of porous asphalt

Porous asphalt consist of four layers; they are:

Porous asphalt course

This is an open graded asphalt concrete wearing course which is approximately *50.8-101.6 mm* thick laid over a base course of uniformly graded size aggregate. This course consist of little sand or dust, with air void percentage of around 16-25 per cent as compared to the conventional pavement which has 2-3 percentage of air void. In this concrete, 50-100 penetration grade of asphalt is used depending on the surrounding temperature and viscosity characteristics desired.

Filter course

This structural layer is immediately beneath the porous asphalt course with a thickness of *25.4-50.8 mm, consisting of 12.7 mm* crushed stone aggregate. This layer serves as a filter and also provides stability for the reservoir course during the application of asphaltic mix.

Reservoir course

This also refers to as the heart of the system; it is a base of *38.1-76.2 mm* stone of a depth determined by the storage volume needed. In addition to transmitting mechanical loads, the reservoir course stores runoff water until it can infiltrate into the soil. On slopes, reservoir courses at the higher end are not credited with storage capability because of lateral drainage. Where soils have low permeability, the reservoir course thickness should be increased to provide additional storage. With soils composed primarily of clay or silt, the infiltration capacity may be so slow that the soil is unacceptable as a subgrade, necessitating replacement by suitable borrow material. If the natural material beneath is relatively impermeable, then drainage may have to be provided. The drainage may take the form of subsurface drains, French drains or ditch drains.

Non-woven geotextile material

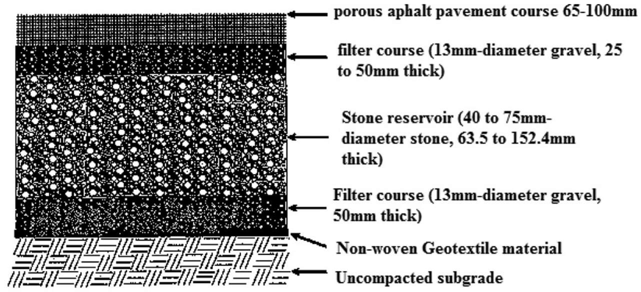
This layer serves a protector to the reservoir course above from contamination and allows water to flows through the soil.

Sub-base

This is the layer under the reservoir base course which drain the water to maintain its bearing strength, that is to say the soil in the sub-base must be permeable to water, do not heave because of freezing or thawing and also do not swell or substantially lose its strength when its wet. But there is a need of proper drainage to meet the requirement (Huber, 2000) (Figure 2).

Even though limited structural information is available, porous pavements have lasted for more than 20 years. For porous pavements carrying light automobile traffic only, the structural requirements are not significant, and the material thicknesses are determined by the hydrological design and minimum thicknesses required for porous asphalts. For porous asphalt pavements expected to carry truck loads, the

Figure 2 Cross-section of porous asphalt



Source: Ferguson, 2005; Michel Legret and Colandini, 1999; M Legret, Nicollet, Miloda, Colandini, and Raimbault, 1999

Table I Recommended layer coefficients

Material layer	Structural coefficient
Porous asphalt	0.40-0.42
Asphalt-treated permeable base (ATPB)	0.30-0.35
Porous aggregate base (stone recharge bed)	0.10-0.14

Source: FHA (2016)

structural design procedures should follow standard AASHTO 93 design procedures. Recommended layer coefficients for porous asphalt pavements are shown in Table I. Recommended minimum thickness of the compacted porous asphalt layer for different truck loadings are shown in Figure 3 (FHA, 2016).

Porous asphalt mixture properties and characteristics

Porous asphalt mixtures are designed using the superpave (50 gyrations) or marshall (35 blows per side) methods with requirements for higher air voids and low draindown to assure permeability and performance. To reduce draindown and provide resistance to scuffing, mixes are typically designed with polymer-modified binders. Fibers are often added to the mix to reduce draindown. Many states have specification for porous asphalt/open-graded friction courses and asphalt-treated permeable bases that may be used in specifying mixes for porous asphalt pavements, as shown in Table II below.

Porous asphalt mixture test methods

Because porous asphalt surfaces do not hold water, they have a very low risk of moisture-relate damage. Despite this, it is still recommended to add an anti-stripping agent to the mix if it would be required for dense-graded mixtures using the same materials. If there is no history determining whether an anti-stripping agent would be required, then a moisture susceptibility test may be run on a dense-graded mix with the same aggregate and binder (ASTM D7064M-08). There are a number of guides and specifications available for porous asphalt mixes, including Hansen (2008), UNHSC (2014) and Mallick *et al.* (2000), as well as guidance from state DOTs, AASHTO, ASTM and state asphalt pavement associations. Test methods for porous asphalt are as follows:

- AASHTO T 269-11/ASTM D3203M-11 standard test method for per cent air voids in compacted dense and open bituminous paving mixtures;

Figure 3 Recommended minimum thickness of the compacted porous asphalt layer for different loadings

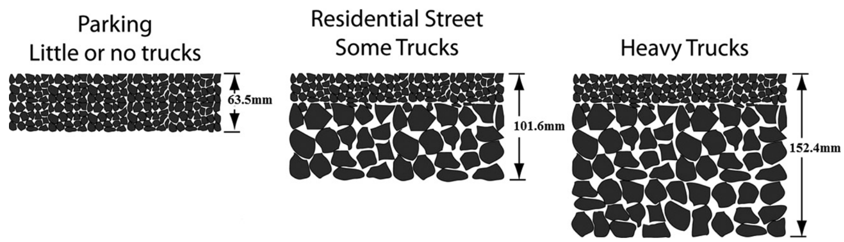


Figure 4 Examples of designs using a stone edge or drop inlet to manage overflows

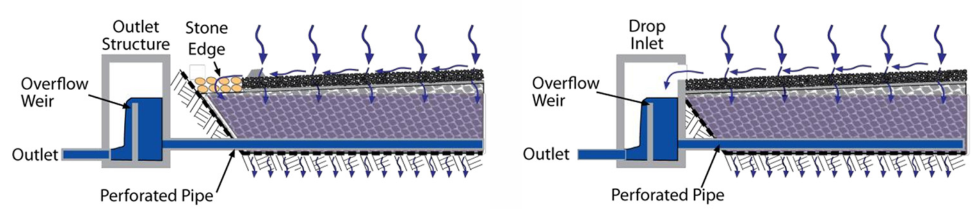


Table II Specifying mixes for porous asphalt pavements

Mix properties	Requirement
Air voids (AASHTO T 269-11/ASTM D3203M-11)	> 16%
Binder grade	Minimum high temperature of 64°C is recommended. PG 64-28 or PG 70-28 modified binders can be specified in an effort to provide improved mix stability and durability
Draindown (AASHTO T 305-09/ASTM 6390-11)	= 0.3%
Asphalt content (by weight of total mix)	For 9.5 mm nominal aggregate size porous asphalt mixes, the recommended minimum asphalt content is 5.75% by weight of mix. In rare cases, this may not be possible. In these cases, the Cantabro test (ASTM D7064M-08) should be run to assure durability. For larger stone mixes, the asphalt content will decrease. The asphalt content should be the highest possible without exceeding draindown requirements.
Maximum aggregate size	The maximum recommend aggregate size for surfaces is 12.5 mm nominal aggregate size. Larger nominal aggregate size mixes are recommended for base courses
Tensile strength ratio (TSR @ 50 gyrations and design air voids) [ASTM D4867]	70% min

- AASHTO T 331-13/ASTM D6857M-11 standard test method for maximum specific gravity and density of bituminous paving mixtures using automatic vacuum sealing method;
- AASHTO T 305-09/ASTM D6390-11 standard test method for the determination of drain down characteristics in uncompact asphalt mixtures; and
- ASTM D7064M-08(2013) standard practice for open-graded friction course (OGFC) mix design (Cantabro test).

How it works

Porous asphalt mix has a higher concentration of coarse aggregate than fine aggregates as in conventional pavement; this is achieved by straight forward sieving of the aggregates, thus allowing the water to infiltrates through it. A bed of uniformly distributed clean washed graded aggregates which provides large percentage of air voids underneath the pavement. Geotextile filer fabric is used as a layer that separates the stone bed from the uncompacted subgrade, thus preventing the fines from moving into the bed. The void space in the stone serves as storage for the storm water which is held and infiltrates slowly into the underlying soil. The stone bed is usually 18-36 inches deep depending on the requirements for the storage of the storm water and site grading. The good structural base provided by the depth reduced the cracking and pothole formation problems (Scholz and Grabowiecki, 2007). Most porous pavements are not designed to store and infiltrate the maximum precipitation at the site; therefore, overflow should be added in the design to prevent stored storm-water from reaching the surface layers. This will typically involve perforated pipes in the stone reservoir that are connected to the discharge pipe, as shown in Figure 4. It is also recommended that an alternative or additional path for storm-water to enter the stone reservoir be provided in case the surface should become plugged. Figure 4 below shows examples of designs using a stone edge or drop inlet to manage overflows (FHA, 2016).

Benefits of porous asphalt pavement

Safety improvement

Water easily enters in the pavement and is removed from the surface through the interconnected voids. As a result of that, the permeability coefficient of porous asphalt pavement (air voids is 17-23 per cent) is greater than 2.0 × 10-2 and 2000 ml/min, which is far more than that of the conventional asphalt pavement. If there is excess water on the surface, then the surface water will be removed in time which in turns improves the performance, and safety porous asphalt has good resistance to cracking at low temperature and good stability at high temperature. Although it has poor water stability and anti-fatigue performance, it can also meet the requirements of current technical specification (Jiang *et al.*, 2007).

Skid resistance

Porous asphalt pavement enhances friction and visibility in wet weather. Because of its thick bitumen membrane, at the initial stage after construction, it has a low skid resistance which later becomes maximum, which later will decline or be at a stable level in the following years (Jiang *et al.*, 2007).

Environmental benefits

One of the important benefits of porous asphalt is its ability to reduce the capacity of noise or, in other words, control highway noise levels. Because of the large air voids percentage in porous asphalt, sound absorption coefficient is great which effectively reduces vehicles reflection noise and pollution along the road. A study found that the maximum frequency of sound level for porous asphalt pavement is 500-600 hz and 1,000-1,250 hz for conventional pavement (Jiang *et al.*, 2007; Scholz and Grabowiecki, 2007).

Economic benefit

Because of its smoothness, fuel consumption is reduced by 2 per cent when porous asphalt pavement is used. Reduction in the rate of tire wear on porous asphalt was suggested based on a decrease in tire stresses generated by the improved macrotexture of this type of mixture. In addition, porous asphalt mixture can renew existing surfaces in terms of functional performance (i.e. riding quality) (USEPA, 1999). When porous asphalt overlays are used as wearing courses and placed on structurally sound pavements, they can rectify/retard the following distresses (Elvik *et al.*, 2009; Liu and Cao, 2009):

- ravelling;
- oxidation;
- skid problems;
- hydroplaning;
- splash and spray; and
- flushing and bleeding reflective cracking.

Limitation of porous asphalt porous pavement

In certain road condition, the porous asphalt layer becomes unsuitable, such as in the following conditions:

- The pavement structural strength is substandard – this is because porous asphalt is a non-structural layer.
- There is considerable traction because of sudden acceleration, braking and turning activities like at major junctions. This is because the aggregates could be stripped from the surface.
- There are tight radius curves and loops of radius less than 75 meters.
- The gradient of the road exceeding 10 meters.
- Free drainage cannot be accommodated along the road shoulders.
- Length of the roads less than 100 meters. This is because the tendency of the splash and spray being carried from adjacent surface is a probability. So that, if the road is less than 100 meters, then the effectiveness of porous asphalt in reducing splash and spray could be very low.
- Traffic volume – road with traffic volume of more than 4,000 commercial vehicles per lane per day. This is because the porous asphalt surface can be easily damaged.
- Slow speed – road with relatively slow moving vehicle of less than 40 km/hr. This is because at this speed level, the porous asphalt is not beneficial in reducing spray or noise, because those effects can be neglected.
- Areas with severe turning movements: Areas that experience short radius turning are not recommended for placement of porous asphalt. These areas include parking areas, intersections, ramp terminals, truck stops and weigh stations.
- Muddy and sandy areas: *porous asphalt* should not be used in areas where mud or sand may be tracked onto the pavement from unsurfaced side roads (roadways that experience significant agricultural traffic or near beaches and sand dunes). The fines from mud and sand can fill the voids and reduce the drainage capacity of the porous asphalt.
- Areas prone to oil and fuel dripping: *porous asphalt* should not be used in areas where dripping of oil or fuel from slow or stopped vehicles could cause the surface to soften and deteriorate rapidly. These areas include intersections.
- Bridge decks: *porous asphalt* should not be used to overlay a bridge deck.
- Localized areas to be removed and replaced: porous asphalt should not be placed in areas where a bathtub effect may be created. When sections of conventional pavement are removed, conventional pavement should be used as a replacement material before overlaying with porous asphalt.
- Cold climatic areas: porous asphalt should not be placed in cold weather. Porous asphalt with polymer modified binder must be used when the atmospheric temperature is between 45 and 55°F or when the minimum mix laydown temperature cannot be achieved with conventional (unmodified) binders.
- Porous asphalt mixture have high initial cost, about 30 to 35 per cent higher than that of conventional pavement mixture. These costs are balanced by long-term lower cost and maintenance savings. Extra component in the mix, the equipment needed to introduce these components into the mix production, increased temperature of production and slower production rates also contribute to increase production cost. Also, costs will vary with the use of modifiers (polymer and asphalt rubber), thickness of the overlay and expected life under the conditions in which it is used. Using modified asphalt binders tends to increase the life expectancy of porous asphalt mixture. When user cost and traffic delays are removed, it proved to be much cheaper to use porous asphalt than conventional pavement when considering the life span of the asphalt pavement.

In addition, the porous asphalt may also exhibit the following limitations:

- increase the potential for stripping of the surface and underlying pavement;
- require special snow and ice control methods and generally remain icy longer;
- require special patching and rehabilitation techniques;
- do not add structural value to the pavement (their performance is governed by the condition of underlying pavement); and
- may ravel and shove when used at intersections, locations with heavy turning movements, ramp terminals, curbed sections and other adverse geometric locations.

Table III Pollutants and sources in highway runoff

Constituent	Source
Particulate	Pavement wear, vehicles, atmospheric deposition, maintenance activities
Nitrogen, phosphorus	Atmospheric deposition and fertilizer application
Lead	Leaded gasoline from auto exhausts and tire wear
Zinc	Tire wear, motor oil and grease
Iron	Auto body rust, steel highway structures such as bridges and guardrails and moving engine parts
Copper	Metal plating, bearing and brushing wear, moving engine parts, brake lining wear, fungicides and insecticides
Cadmium	Tire wear and insecticide application
Chromium	Metal plating, moving engine parts and brake lining wear
Nickel	Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear and asphalt paving
Manganese	Moving engine parts
Cyanide	Anti-caking compounds used to keep deicing salts granular
Sodium, calcium, chloride	Deicing salts
Sulphates	Roadway beds, fuel and deicing salts
Petroleum	Spill, leaks, antifreeze and hydraulic fluids and asphalt surface leachate

Sources: Gilbert and Clausen, 2006; Kayhanian *et al.*, 2012; Scholz and Grabowiecki, 2007; Stotz and Krauth, 1994

Pollutants and sources in highway runoff

Storm-water surface runoff includes separately sewered discharges from impervious surfaces and overland flows from open spaces, parks/gardens, road verges and construction sites. Reduction of storm-water pollution can be achieved by the use of porous asphalt pavement. However, porous asphalt pavement alone may not eliminate the discharged pollutant load. To accomplish pollutant reduction and develop a cost-effective treatment, knowledge of runoff water quality characteristics is required. But the priority objectives must be to avoid or minimize increased flooding and pollution risks while increasing performance efficiency and enhancing local environmental quality-of-life. The identification and evaluation of a range of technical (e.g. storm-water best management practices; BMPs) and planning (e.g. low impact development) approaches to manage USW under differing climate and urban change scenarios has been the subject of considerable research from a water quantity perspective (Houle *et al.*, 2009; Lundy *et al.*, 2012).

Water quality control is usually defined by identified pollutants of concern and the desired level of removal expected. Typical pollutants of concern associated with management objectives include suspended sediments, nitrogen and phosphorus and traces of heavy metals. Because of high levels of imperviousness and road density, storm-water from ultra-urban areas will likely contain similar loadings of some pollutants from commercial or industrial land use activities as shown in Table I (Gilbert and Clausen, 2006; Kayhanian *et al.*, 2012; Scholz and Grabowiecki, 2007; Stotz and Krauth, 1994) (Table III).

Conclusion

Most permeable pavement depends on sedimentation and infiltration/filtration processes to remove pollutants from

Table IV General transport and pollutant removal effectiveness (%)

Pollutants	Primary transport phase(s)	Pollutant removal effectiveness (%)	References
Suspended solids	Particulate	82-99	Legret and Colandini (1999), Roseen *et al.* (2011), Rushton (2001), Scholz and Grabowiecki (2007)
Nutrients	Particulate/dissolved	60-71 for particulate Not available for dissolve	Legret and Colandini (1999) Gilbert and Clausen (2006), Roseen *et al.* (2011), Rushton (2001)
Trace metals	Particulate/dissolved	33-99	Legret *et al.* (1999)
Trace organics	Particulate/dissolved	Not available	
Oil and grease	Petroleum hydrocarbon in diesel range	99	Roseen *et al.* (2007)
Bacteria	Particulate	Not available	

Sources: Boving *et al.*, 2004; Brown, 2003; Rushton, 2001 storm-water but which may have little effect when dealing with dissolved and highly mobile pollutants. Porous asphalt pavement, on the other hand, have some of the possible benefits over conventional pavement include: the ability to remove suspended solids as well as those pollutants that can be removed by physical processes (e.g. sedimentation and filtration), including oil and grease, metals, nutrients and trace organics associated with suspended solids. The pollutant removal effectiveness of porous asphalt pavement as shown in Table II on a wide range of potentially harmful, primarily trace organic pollutants is not known (Boving *et al.*, 2004; Brown, 2003; Rushton, 2001). The degree of pollutant removal is related to the amount of runoff which exfiltrates the subsoils. This practice may also help reduce land consumption by reducing the need for traditional storm-water management structures. However, on the other hand, the priority objectives which is minimizing increased flooding and pollution risks while increasing performance efficiency and enhancing local environmental quality-of-life is achieved (Barrett *et al.*, 2006; Li *et al.*, 2013; Lundy *et al.*, 2012; Marsalek and Chocat, 2002; Roseen *et al.*, 2011) (Table IV).

Recommendations

Porous asphalt pavements should never be seal coated or crack sealed. If patching is necessary, then conventional mixes may be used if less than 10 per cent of the pavement area d is affected. Also, an understanding of the processes underpinning the environmental benefits of porous asphalt pavements is essential to optimize the operation of the system.

Additional research should be conducted to:

- develop improved mix-design procedures to reduce the potential for clogging and scuffing of these pavements;
- determine structural values for the porous asphalt mixes and stone reservoir course;
- determine what procedures on rehabilitation of porous asphalt pavements (i.e. milling, cleaning and tack coat) may be used to rehabilitate these surfaces; and
- investigate the removal microbiological effects, hydrocarbons, heavy metals and nutrients (i.e. nitrogen and phosphorus).

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