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# Review of permeable pavement systems

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**Abstract**

The purpose of this review paper is to summarise the wide-range but diffuse literature on predominantly permeable pavement systems (PPS), highlight current trends in research and industry, and to recommend future areas of research and development. The development of PPS as an integral part of sustainable drainage systems is reviewed in the context of traditional and modern urban drainage. Particular emphasise is given to detailed design, maintenance and water quality control aspects. The most important target pollutants are hydrocarbons, heavy metals and nutrients (i.e. nitrogen and phosphorus). The advantages and disadvantages of different PPS are discussed with the help of recent case studies. The latest innovations are highlighted and explained, and their potential for further research work is outlined. Recent research on the development of a combined geothermal heating and cooling, water treatment, and recycling pavement system is promising.


*Keywords:* Design; Geotextile; Geothermal heating and cooling system; Permeable pavement; Porous pavement; Sustainable drainage system

## 1. Sustainable drainage systems (SUDS)

### 1.1. Sustainability

Most cities of the developed world rely on pipe network systems, which have frequently been developed in the 19th century. Traditional systems capture storm runoff, and subsequently distribute it to nearby watercourses or sewer systems. Some of these systems have become ineffective and inefficient. Furthermore, they are usually very expensive [1,2].

Instead of focussing on 'end-of-pipe' treatment, SUDS challenge the traditional approach of wastewater treatment by optimising the resource utilisation and development of novel and more productive technologies [3].

### 1.2. Harvesting, storing, treating and recycling of runoff

The management of runoff in urban areas has taken a 'green' approach due to the emergence of SUDS, which collect, store, treat, redistribute and/or recycle water. Examples of these techniques are swales, filter strips, wetlands and ponds [4].

A central element of sustainable storm water management is the utilisation of storm water as a resource [4]. In countries such as Norway, Sweden and Denmark, water in open systems is used recreationally and in the development of ecosystems and landscapes.

## 2. Pavement systems

### 2.1. Applications and challenges

Permeable pavement systems (PPS) are suitable for a wide variety of residential, commercial (e.g. Fig. 1) and industrial applications, yet are confined to light duty and infrequent usage, even though the capabilities of these systems allow for a much wider range of usage. Where there is any concern about the possible migration of pollutants into the groundwater, PPS should be constructed with an impermeable membrane, and the treated storm water should subsequently be discharged into a

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Fig. 1. Modern permeable pavement tanked system example with water recycling facility at Sanders Garden World (near Bristol, England, UK); picture taken by Mr. P. Smith in 2001.

suitable drainage system [5]. Common applications of PPS are as follows:

- vehicular access: residential driveways, service and access driveways, roadway shoulders, crossovers, fire lanes and utility access;
- slope stabilisation and erosion control;
- golf courses (cart paths and parking);
- parking (church, employee, overflow and event);
- pedestrian access (Fig. 1);
- bicycle and equestrian trails; and
- land irrigation.

### 2.2. Permeable pavements

SUDS such as PPS (Fig. 2) have evolved from a growing recognition that traditional storm water management systems have limitations due to growing rates and volumes of storm water runoff, mainly caused by increased urbanisation and changing weather patterns [1,6].

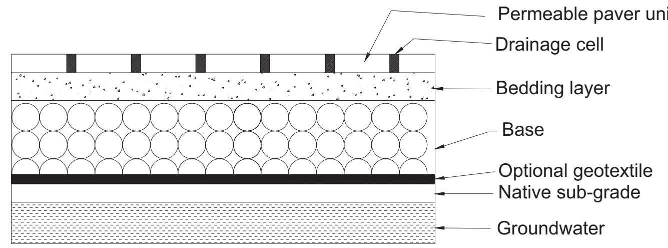


Fig. 2. Typical schematic layout of a permeable pavement system.

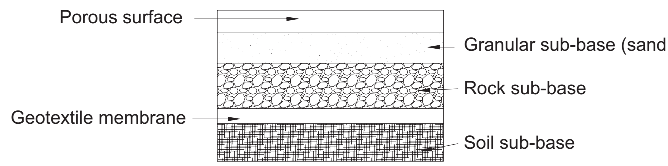


Fig. 3. Typical schematic layout of a porous pavement system.

Permeable pavement designs vary greatly. For example, Fig. 1 shows a modern permeable pavement tanked system example. The general principle of PPS is simply to collect, treat and infiltrate freely any surface runoff to support groundwater recharge. In comparison to traditional drainage systems, storm water retention and infiltration is a sustainable and cost effective process, which is suitable for urban areas [6,7]. Moreover, PPS have many potential benefits such as reduction of runoff, recharging of groundwater, saving water by recycling and prevention of pollution [8].

PPS have not only been established as a SUDS solution, but also as a technology for pollutant control concerning surface runoff from areas used as roads or parking spaces, where contaminated water may infiltrate into the underlying soil. Harmful pollutants such as hydrocarbons and heavy metals in surface runoff have the potential to endanger soil and groundwater resources when they are not sufficiently biodegraded and/or removed during infiltration [9,10].

Reductions in suspended solids, biochemical oxygen demand, chemical oxygen demand and ammonia levels in comparison to highway gullies not only demonstrate the high treatment efficiency of PPS, but also that there is no need for frequent maintenance, unlike with gully pots [8].

Moreover, hydrocarbon pollution and mineral oil deposition onto urban surfaces have been problems most effectively addressed by PPS. Research has also shown that the structure itself can be used as an effective in-situ aerobic bioreactor [11].

### 2.3. Porous pavements

The focus of this review paper is on PPS. However, porous pavements (Fig. 3) are also briefly reviewed to provide the reader with a more comprehensive overview of various pavement systems. Porous pavements have been developed to reduce the runoff rates and growing volumes of storm water collected in urbanised areas. They should meet storm water demands while providing a hard surface, which can be utilised in urban areas [1,12].

Porous asphalt or macadam pavement looks similar to conventional asphalt, but is relatively porous. It consists of open-graded asphalt and concrete over an open-graded aggregate base located above well-draining soil.

Porous concrete pavement contains aggregates and a Portland cement binder. The porosity is provided by the omission of fine aggregates. Modular interlocking concrete blocks of the internal drainage cell type are pre-cast or cast-in-place lattice or castellated pavers of concrete or plastic, which contain open cells. Soil mixed with grass seeds or porous aggregates usually fill the cells.

Modular interlocking concrete blocks with external open drainage cells are also available on the market. Open cells are formed when blocks are assembled in an interlocking manner and filled with clean gravel.

Block paving stones made of specially designed porous concrete (i.e. polymer-modified porous concrete) exhibit better fatigue behaviour than those without polymers. Yet it has been shown that these improvements decrease for low values of stress levels, and sometimes appear to be negligible in the case of traffic loads on main and highway roads [11].

These concrete products can function as pollution sinks, because of their particle retention capacity during filtration. The high porosity of the special concrete leads to good infiltration and air exchange rates. Filtered out pollutants can sometimes be removed by cleaning of the pavement [10].

Porous asphalt and porous concrete pavement systems are prone to clogging usually within three years after installation. Due to clogging of the voids, these systems can experience a loss of porosity. The main causes of clogging are due to:

- sediment being ground into the porous pavement by traffic before being washed off;
- waterborne sediment, which drains onto pavements and clogs pores before being washed off; and
- shear stress caused by numerous breaking actions of vehicles at the same spot, which results in collapsing pores.

Once totally clogged, these systems have to be removed entirely and subsequently replaced. Frequent replacement renders these types of systems impractical and expensive. Modular interlocking concrete blocks have also the potential to be clogged by sediment and produce a low-quality effluent. Therefore, PPS are preferred for most applications.

## 3. Design

### 3.1. Lifespan

The lifespan of porous asphalt, porous pavement or permeable surfaces, in general, depends predominantly on the size of the air voids in the media. The more possibilities for oxidation, the less durability can be achieved [13].

It can be expected that the life of a PPS is shorter than that of an impermeable pavement due to deterioration by runoff, air infiltration, and subsequent stripping and oxidation, as well as hardening of binder. Recent work has indicated that coarsely graded Superpave mixes can be excessively permeable to water at air void levels of approximately 6% [14].

Four commercially available PPS were evaluated by Booth et al. [15] after six years of daily parking usage for structural durability, ability to infiltrate precipitation, and impacts on infiltrate water quality. All pavement systems showed no major signs of wear. Virtually all rainwater infiltrated through the PPS, with almost no surface runoff. The infiltrated water had significantly lower levels of copper and zinc than the direct surface runoff from the asphalt area.

### 3.2. Aggregate components

The PPS (Fig. 2) comprises four distinct components [16]:

- pavers (e.g. Fig. 1) and bedding layer;
- unsaturated zone of the base material;
- saturated zone of the base material; and
- sub-grade.

Various aggregates can be incorporated into PPS. For example, Nishigaki [17] described specially designed blocks for permeable paving using recycled melted slag. No metal leaching was detected in practise.

### 3.3. Geotextiles

Geotextiles help to prevent sand from migrating into the base of PPS. In a permeable bituminous-stabilized base course, the presence of geotextile helps to reduce the rutting depth and rate of block breakage, maintaining a good level of pavement serviceability such as easy cleaning. A geotextile with a fibre area weight of $60\,g/m^2$ is usually applied [18]. Furthermore, most geotextiles can help to retain and degrade oil, if clogging (e.g. silting) is not a problem [19].

### 3.4. Hydrology and hydraulics

Tests have shown that evaporation, drainage and retention within the permeable structures were mainly influenced by the particle size distribution of the bedding material, and by the retention of water in the surface blocks [7,12].

Movement of water through the porous pavement installation is controlled by surface runoff, infiltration through the pavement stones, percolation through the unsaturated zone, lateral drainage at the base and deep percolation through the sub-grade. There are three possible fates for precipitation reaching the surface of a PPS installation [12,16]:

- infiltration to the base material;
- evaporation; and
- runoff (overland flow).

In designing a permeable pavement installation, it is fundamentally important to provide and maintain surface infiltration and storage capacity to allow an adequate volume of storm water to be captured and treated by the facility. James and von Langsdorf [16] describe the underlying method and function of a computer programme, which uses the United States Environmental Protection Agency Storm Water Management Model for the hydraulic design of permeable pavement installations.

In comparison to conventional asphalts, permeable and porous pavements provide more effective peak flow reductions (up to 42%) and longer discharging times. There is also a significant reduction of evaporation and surface water splashing [12,15,20,21].

### 3.5. Maintenance to enhance infiltration

Infiltration through the permeable pavement stones and the bedding layer is usually modelled using the complex Green–Ampt equations, which have physically based parameters that can be predicted. Infiltration is thus related to the volume of water infiltrated, and to the moisture conditions in the pavers and bedding layer [16].

Green and Ampt provided an approach that is based on fundamental physics but also gives results that match empirical observations in the laboratory. However, the corresponding set of equations is difficult to apply to the field or landscape scale; e.g. the suction forces at the wetting front cannot be accurately described. The presentation of all relevant equations is beyond the scope of this review paper.

Percolation or trickling represents the vertical flow (by gravity alone) of water from the unsaturated zone (i.e. voids filled with air) to the saturated zone (i.e. voids filled with water) of the base layer, and is the only inflow source to the saturated zone assuming that there is no water exchange with the surrounding environment below the ground level. Base layer discharge represents lateral flow from the saturated zone of the base to the receiving water. Deep percolation represents a lumped sink term for not quantified losses from the saturated zone of the base. Two primary losses are assumed to be percolation through the confining layer and lateral outflow to somewhere other than the receiving water [16].

Concrete grid pavers and permeable interlocking concrete pavers were tested with pavement ages ranging between 0.5 and 20 days. Analysis of the data showed that maintenance (i.e. cleaning of pavers at the end of each experiment) improved permeability on 13 out of 14 sites at a confidence level of 99.8%. Sites built in close proximity to loose fine particles had infiltration rates significantly less than sites free of loose fines. Even the minimum existing infiltration rates were comparable to those of a grassed sandy loam soil [22]. Furthermore, the impact of maintenance on the environment was not sufficiently discussed.

Furthermore, the surface infiltration rates of 48 PPS sites were tested in North Carolina, Maryland, Virginia and Delaware. Maintenance consisted of removing residual material located on top of the PPS. The locations of PPS and their maintenance types and regimes were critical to maintaining high surface infiltration rates [22].

Caoi et al. [23] provided a method to determine the amount of infiltration liquid, and the storage capacity of a permeable base relative to the time of retention and degree of saturation associated with the characteristics of the base. Their guidelines contain a step-by-step process for engineers to select the best pavement option in terms of base materials and gradations for the given drainage, sub-grade strength conditions, and the criteria for maximum allowable rutting.

Infiltration supports groundwater recharge, decreases groundwater salinity, allows smaller diameters for sewers (resulting in cost reduction) and improves water quality of receiving waters, because pollutants and high peak flow are effectively controlled. On the other hand, pollutants in runoff originating from domestic and industrial emissions, and traffic threaten soil and groundwater, if they are not removed from runoff before it infiltrates into the ground [10,12].

## 4. Water quality

### 4.1. Pollutants

Impervious surfaces have a high potential for introducing pollution to watercourses. Possible water quality variables of concern include the following [12,24,25]:

- sediment and suspended solids (including phosphorus and some metals);
- organic waste with high biochemical oxygen demand;
- dissolved nutrients and pollutants (including nitrogen, heavy metals, solvents, herbicides and pesticides);
- oil and grease; and
- faecal pathogens.

Permeable pavements have a good track record at removing suspended solids and nitrogen. However, PPS, which do not rely on below ground infiltration and the use of an underdrain system, will not be successful in the removal of nitrogen. When an underdrain system is incorporated into the pavement design, storm water tends not to infiltrate into the soil, but into the underdrain, where it can be denitrified or removed by plant uptake [25].

Along with atmospheric contaminants, harmful pollutants can also be emitted from roof material and road surfaces. Hydrocarbons, lead and copper show the highest pollutant concentrations. Rainwater gutters and associated pipes often consist of zinc-coated sheets or copper. Metal roofs usually show high concentrations of heavy metals in the corresponding runoff, if not cleaned prior to discharge [6,12].

Dierkes et al. [6] summarised possible ranges of pollutant concentrations in rain, and roof and road runoff, taken from more than 60 sites throughout Europe. Rain may contain 5-day biochemical oxygen demand (1–2 mg/l), sulphate (0.56–14.40 mg/l), chloride (0.2–5.2 mg/l), ammonia (0.1–2.0 mg/l), nitrate (0.l–7.4 mg/l), total phosphate (0.01–0.19 mg/l), copper (1–355 μg/l) and zinc (5–235 μg/l). Phosphorous and inorganic nitrogen concentrations are generally lower than those of organic substances. These pollutants are potentially harmful to receiving waters. Runoff from roads usually contains higher pollutant concentrations than roof runoff [6].

### 4.2. Hydrocarbons

Oil and diesel fuel contamination is frequently detected on asphalt and other non-permeable surfaces. In comparison, these contaminants were not detected on PPS surfaces assessed by Bratterbo and Booth [9]. Hydrocarbons can endanger soil and groundwater, if they are not removed sufficiently during infiltration through the surface layer [10]. Many pollutants such as polycyclic aromatic hydrocarbons, metals, phosphorous and organic compounds are absorbed onto suspended solids. Models have been designed to estimate the suspended solids load and its dynamics during rainfall events, leading to better understanding of receiving waters being polluted by hydrocarbons [26].

Concerning various pavement systems, Booth et al. [15] showed that infiltrated water had significantly lower levels of copper and zinc in comparison to the direct surface runoff from the asphalt area. Motor oil was detected in 89% of samples from the asphalt runoff, but not in any outflow water sample from the PPS. Diesel fuel was not detected in any sample. Infiltrate measured five years earlier displayed significantly higher concentrations of zinc, and significantly lower concentrations of copper and lead [15].

Permeable pavements can operate as efficient hydrocarbon traps and powerful in-situ bioreactors. Coupe et al. [27] found out that a PPS specifically inoculated with hydrocarbon-degrading microorganisms does not successfully retain a viable population of organisms for the purpose of increased hydrocarbon degradation over many years. Naturally developed microbial communities (i.e. no inoculation with allochthonous microorganisms) degrade oil successfully.

For the successful biodegradation of polycyclic aromatic hydrocarbons, certain environmental conditions need to be met. Degradation takes place when prolonged aerobic, sulphate reducing and denitrifying conditions occur [28]. Very large hydrocarbon spills can be contained due to absorption processes within the pavement [19].

Wilson et al. [5] incorporated an oil interceptor into a porous surface construction. Tests were carried out for worst-case scenarios such as the worst possible combined pollution and rainfall event to assess how the system retains pollutants within its structure. The results successfully demonstrated that this system can retain hydrocarbons, and can therefore offer outflow with improved water quality. However, where certain detergents are present in the pavement system, they can cause contamination of the outflow water, which may require secondary treatment to improve its water quality.

### 4.3. Metals

Studies have shown an improvement of water quality by filtration through PPS, which work well in removing suspended solids and particularly heavy metals from runoff. For example, Legret et al. [29] showed that suspended solids and lead can be reduced by PPS up to 64% and 79%, respectively.

Kellems [30] showed that enhanced filtration using organic media was an effective alternative to chemical precipitation for the treatment of storm water. Filtration through a specific adsorbent organic medium can remove about 95% of dissolved copper and zinc.

In comparison to pavements made of asphalt, concentrations of zinc, copper and lead were significantly lower on permeable structures [9,12]. Lead concentrations were in fact undetectable. A PPS should regularly be kept clean to prevent clogging.

Generally, PPS are efficient in trapping dissolved heavy metals in surface runoff [10]. However, not all pavers and joint fillings have the ability to trap dissolved heavy metals. Pavements with large joints for infiltration must have a suitable joint filling. Otherwise, metals will pass through them, and may subsequently enter groundwater resources.

Particles usually accumulate in geotextiles and on pavement surfaces. Geotextiles usually separate micropollutants such as cadmium, zinc and copper from the underlying soil, therefore preventing groundwater from becoming contaminated [29].

### 4.4. Microbiology

PPS are powerful in-situ bioreactors, which can reduce hydrocarbon contamination by 98.7%. Biodegradation in PPS is enhanced by bacteria and fungi [27]. When inoculated with microorganisms, the protozoan population diversity within a PPS increases more rapidly than in a similar non-inoculated system. Pavements contain testate amoebae, ciliates, flagellates and gymnamoebae. The understanding of microbial biodiversity helps to interpret biodegradation mechanisms [27].

PPS have the capacity to degrade large quantities of clean motor oil. Bio-treat HD, a commercially available oil degrading microbial mixture, will not degrade oil any better that the local microbial biomass established within the pavement over a long period of time. However, the local microbial biomass can only achieve high degradation rates, if there is adequate supply of nutrients (i.e. nitrogen and phosphorous) in the feed. Monitoring of biofilm development through scanning electron microscopy has revealed that a PPS can obtain a high degree of biodiversity due to the development of complex microbial compositions [31].

The assessment of the microbiological water quality has been an important process in preventing waterborne diseases. The two most common alternate tests carried out are for coliforms and *Escherichia coli*, or faecal coliforms [32].

Total coliforms, faecal coliforms, faecal streptococci, heterotrophs, fungi, *Pseudomonas aeruginosa*, *Leptospira*, salmonellae and viruses are often analysed in an attempt to determine the temporal distribution of bacterial pathogens and viruses in storm water runoff. However, findings usually show that it is not possible to accurately predict the time when peak microbial populations including human pathogens occur in runoff waters.

## 5. Innovations and future research

Concerning porous pavements, silica fume and super plasticizer can be added to standard porous concrete ingredients. This usually improves the compressive strength of the porous pavement to allow for higher loads depending on the application [33].

With respect to PPS, an additional layer of heat-bonded geotextile was introduced to the Formpave sub-base [19]. This liner slowed down the release of small oil spillages, and their subsequent transport through the system. In case of an emergency, however, this solution cannot be used to protect large volumes of released oil, although the oil trap may significantly reduce the released amount of oil.

Furthermore, the authors of this paper have recently worked with Formpave and Water Furnace Europe to develop a heating/cooling system, which can be installed within the sub-base of modern PPS (e.g. Figs. 1 and 4). The energy gained from the below-ground pump can be used for heating or cooling buildings. Natural energy can be used to heat water and subsequently reduce industrial and domestic energy bills. The system is safe, reliable and energy efficient, because heat energy is transferred from the earth to heat and cool work and domestic environments, which would otherwise rely on fossil fuels that are becoming scarce and more expensive. The research focuses also on improving the growth of microorganisms during artificial temperature fluctuations induced by the heat pump.

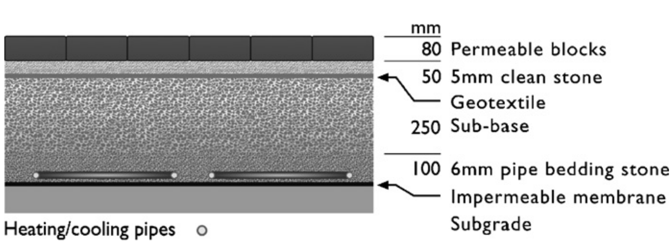


Fig. 4. Tanked permeable pavement system including a heating/cooling element.

Further research on the short- and long-term effects of contaminants that remain in the PPS should be undertaken. The self-sustainability of these relatively new systems in comparison to traditional pavements requires further assessment. Moreover, the long-term impact of PPS on the environment is still unclear.

Finally, as PPS are becoming established as environmental friendly engineering techniques, there is a need for the development of simple computer-based decision support tools for engineers and planners. Most recent attempts to incorporate PPS into a SUDS decision support model were made by the lead author [2, 34].

## 6. Conclusions

This review paper summarised the diffuse literature on permeable and porous pavement systems. Permeable pavement systems (PPS) have become an important integral part of sustainable urban drainage systems despite the lack of corresponding high-quality research in comparison to other research areas. In contrast, porous pavements are usually associated with clogging problems and are therefore not as much applied in practise as PPS.

Design, maintenance and water quality control aspects relevant to the practitioner were outlined for permeable and porous pavement systems. The detailed design and specific maintenance requirements for PPS do not allow for the specification of general guidelines. Research is therefore likely to be empirical and of applied nature in the future.

The most important target pollutants were hydrocarbons, heavy metals and nutrients (i.e. nitrogen and phosphorus). More recent focus is on faecal coliforms introduced to PPS via dog droppings. The advantages and disadvantages of different PPS were discussed with the help of case studies concerning different water quality aspects.

Recent innovations were highlighted and explained, and their potential for further research work was outlined. The development of a combined geothermal heating and cooling, water treatment and recycling pavement system is promising, and is therefore encouraged. Further work on the assessment of the self-sustainability and sustainability of PPS is also encouraged.

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