

Permeable Pavement as a Sustainable Management Option for Highway Stormwater and Safe Use of Roadways



MTI WP Report 12-13



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WP REPORT 12-13

PERMEABLE PAVEMENT AS A SUSTAINABLE MANAGEMENT OPTION FOR HIGHWAY STORMWATER AND SAFE USE OF ROADWAYS

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EXECUTIVE SUMMARY

RESEARCH BACKGROUND AND OBJECTIVE

Urbanization has resulted in the replacement of pervious vegetative lands with impervious surfaces such as pavement, which reduces the area where infiltration to groundwater can occur, thus increasing surface runoff into streams or accumulation of stormwater that can lead to flooding. To protect road pavement and travelers from water-related damage, stormwater must be drained from the roadway. Stormwater runoff from roads is known to contain contaminants. Transportation agencies in the country are required by the Environmental Protection Agency (U.S. EPA) to comply with the National Pollution Discharge Elimination Standard (NPDES). These include planning and design permit requirements for the treatment of stormwater runoff to ensure that rainwater runoff from roads (including local, state, and federal roads) do not carry pollutants into receiving water bodies such as rivers, creeks, lakes, and streams. To comply with the U.S. EPA requirements, transportation agencies must implement Stormwater Best Management Practices (BMPs) to capture and treat stormwater runoff from road surfaces.

One of the BMPs is the use of permeable pavement that allows stormwater to move through the pavement layers (away from the road surface) where it can either infiltrate into the soil and groundwater or drain to the road shoulder where it is collected for treatment as needed. There is limited evidence, however, regarding any traffic safety issues associated with highway stormwater and the type of permeable pavement suitable for various traffic requirements.

The primary objective of this project is to conduct a comprehensive literature review on (1) the effect of stormwater on defects of road surfaces (pavement), (2) traffic safety issues associated with highway stormwater, (3) the use of permeable pavement to manage highway stormwater, and (4) the identification of gaps in the existing literature for further research.

RESEARCH METHODOLOGY

The research team conducted a literature review focusing on the following aspects of permeable pavement in relation to roadway stormwater management:

1. Environmental pollution associated with highway stormwater
2. Stormwater removal from road surfaces
3. Highway stormwater BMPs
4. Stormwater impact on durability of pavements
5. Road-safety impact of accumulated stormwater on pavement surfaces
6. Types of permeable pavement used in sustainable management of highway stormwater

7. Permeable friction course in highway stormwater BMPs

8. Use of roadway shoulders in stormwater management and safety implications

RESEARCH OUTCOME

There are three main groups of permeable paving materials with individual strength characteristics for carrying traffic load: asphalt, concrete and pavers. In addition, there are three words (permeable, porous, and pervious) that all have the same meaning of allowing passage of water due to the presence of voids. With the three main groups of paving materials and the three words that can be used for pavement that allow infiltration of stormwater, there is no uniformity in the use of the phrases “permeable pavement,” “porous pavement,” and “pervious pavement” that clearly define the type of pavement as well as the functional use of the pavement. Some literature tends to use the phrase “porous pavement” to refer to permeable asphalt pavement and the phrase “pervious pavement” to refer to permeable concrete pavement. Also, it is common to find “pavers” being referred to as permeable pavement although pavers are limited in use to walkways, patios and sidewalk. The authors recommend adding the name of the paving material (asphalt, concrete, pavers) to the word “permeable,” “porous,” or “pervious” to eliminate or reduce the confusion associated with current naming of permeable pavement.

The literature review for this report resulted in the following conclusions.

Issues with accumulation stormwater on road surfaces:

1. Accumulation of stormwater on road surfaces results in various forms of pavement damage, reduces skid resistance (friction coefficient) of pavements, causes hydroplaning, and results in splash and spray of road water, all of which lead to car crashes, injuries and fatalities.
2. Draining of stormwater from pavement surfaces is critical for pavement durability as well as the provision of dry pavement surfaces and associated skid resistance for the safety of the traveling public.

Types of permeable pavement:

1. There are three major types of permeable pavement: (a) permeable pavers, (b) pervious concrete pavements, and (c) porous asphalt pavements.
2. Permeable pavers include: (a) interlocking concrete pavers, (b) brick pavers, (c) stone pavers, (d) Grass/turf pavers, (e) grid concrete pavers, and (f) grid plastic pavers.
3. There is no consistency in the literature in the use of the words “pavers,” “pervious,” and “porous.” This confusion is caused by the fact that permeable pavement includes different types of pavers as well as pervious concrete pavements and porous asphalt pavements, and the terms “permeable,” “pervious,” and “porous” all refer to a material with openings that allow the passage of other substances (in this case, water).

Suitable application of permeable pavement:

1. Pavers are limited to areas with light traffic such as walkways, driveways, parking lots, parking areas, alleys, patios, courtyards, and pedestrian plazas.
2. Permeable concrete and permeable asphalt have been used for low-speed and light-traffic pavement
3. Porous Friction Course (PFC), also known as Open-Graded Friction Course (OGFC) is a thin layer of porous Hot-Mix Asphalt (HMA) surface overlay placed on top of impervious pavement where stormwater infiltrates the thin layer of the PFC and moves laterally on top of the impervious layer towards the road shoulder where it is collected and piped for treatment.
4. Permeable pavements have been recommended for use for road shoulders.

Benefits of using permeable pavement in roadway stormwater management:

1. Permeable pavements provide sustainable BMP for roadway stormwater by allowing roadway stormwater to infiltrate and self-drain into the pavement, where it can either flow into the underlying soil or get collected for treatment.
2. Permeable pavements also reduce the concentration of pollutants in the water that passes through their structural layers and also reduce noise created by the interaction of vehicle tires and surfaces.
3. By removing water from the road surfaces, permeable pavements provide safety to the travelling public.

In addition, the following recommendations are made:

Naming of permeable pavement:

1. It is common to find the different pavers as well as pervious concrete and porous asphalt being referred to as permeable pavement in the literature. To reduce confusion, the authors recommend using the following terms: (1) permeable pavers or pervious pavers or porous pavers, (2) permeable concrete or pervious concrete or porous concrete, and (3) permeable asphalt, pervious asphalt or porous asphalt.

Research needs:

1. There is a need to investigate mechanisms responsible for the removal of pollutants by permeable pavement as well as long-term pollution removal and a need for replacement of layer materials due to clogging by suspended solids.
2. There is a need to research the types of highway shoulders being used for collecting stormwater from highway PFC lanes that would allow the road shoulder to continue to provide its intended safety functions.

3. There is a need to investigate appropriate permeable pavements that have the required structural strength to serve as highway shoulder to provide its intended safety functions.
4. There is a need to investigate the impact of stormwater infiltration on the stability of road side-slopes and the safe use of the road clear recovery zone (CRZ).
5. There is a need for test data on the effect of compaction on the strength (stability) and infiltration of permeable shoulders and road side-slopes.
6. There is a need for test data on the impact of stabilization on the strength (stability) and infiltration of permeable shoulders and road side-slopes.

I. INTRODUCTION

BACKGROUND

Accumulation of stormwater on road surfaces causes pavement damage as well as traffic accidents. For these reasons, stormwater is removed from road surfaces using engineered drainage systems. The drained stormwater undergoes some form of treatment prior to discharge into the environment. Vehicles have been noted as a source of stormwater pollution due to the deposition of various pollutants by automobiles on roads and parking lots. These pollutants include chemicals that are present in automobile lubrication oils, antifreeze, gasoline, tire wear and automobile braking systems as well as particulates from the exhaust system. During rain fall events, these pollutants are washed from the road surface and are carried by stormwater runoff into soils, groundwater and surface water.

Transportation agencies in the United States are required by the Environmental Protection Agency (U.S. EPA) to comply with the National Pollution Discharge Elimination Standard (NPDES), including planning and design permit requirements for the treatment of stormwater runoff to ensure that rainwater runoff from roads (including local, states, and federal roads) do not carry pollutants into waterways such as rivers, creeks, lakes, and streams. To comply with U.S. EPA requirements, transportation agencies must install stormwater BMPs to capture and treat stormwater runoff from road surfaces. One of the BMPs is the use of permeable pavements that allow stormwater to move through the pavement layers (away from the road surface) where it can either infiltrate into the soil and groundwater, or drain to the road shoulder where it is collected for treatment as needed.

Concerns have been raised about structural strength of permeable pavement. With an abundance of reports on various types of permeable pavement, there is a need to classify permeable pavement in a uniform manner that will allow for easy identification of the key structural material and suitable application for various traffic requirements. Uniform classification and naming of permeable pavement is important, as the application of permeable pavement ranges from pavers that are used for pedestrian sidewalk and walkways to permeable “asphalt” friction course that is used as a thin top layer of highway pavement.

OBJECTIVE

The primary objective of this project is to conduct a review of the literature to determine the state of the art on (1) the effect of stormwater on defect of road surfaces (pavement), (2) traffic safety issues associated with highway stormwater, (3) the use of permeable pavement in the management of highway stormwater for various traffic requirements, and (4) the identification of gaps in the existing literature for further research.

SCOPE AND METHODOLOGY

This research includes a review of the literature on the use of permeable pavement in highway stormwater management and traffic-safety issues associated with highway stormwater, as well as recommendations for further investigations.

The primary focus of the research was to conduct a comprehensive review of the literature on environmental pollutants in highway stormwater. The literature was also reviewed on the impact of road stormwater on traffic safety and on the management of roadway stormwater using permeable pavement, including the types of permeable pavement and their structural design components. The research was motivated by a report in the literature on adapting full-depth permeable pavement for highway shoulders for stormwater runoff management. The goal was to review the types of permeable pavement to identify their suitability for use in highway shoulders that are often used by heavy vehicles under relatively high speed. To this end, an extensive online literature search was conducted using the Google search engine. The literature search produced the following themes for the research report:

1. Environmental pollution associated with highway stormwater
2. Stormwater removal from road surfaces
3. Highway stormwater BMPs
4. Stormwater impact on durability of pavements
5. Road safety impact of accumulated stormwater on pavement surfaces
6. Types of permeable pavements used in sustainable management of highway stormwater
7. Permeable friction course in highway stormwater BMPs
8. Use of roadway shoulders in stormwater management and safety implication.

Examples of key words and phrases used in the online searches include permeable pavement, types of permeable pavement, effect of stormwater on pavement durability, highway stormwater runoff, highway stormwater quality, highway stormwater management, highway stormwater infiltration, road cross-section and stormwater drainage system, asphalt pavement defects, concrete pavement defects, effect of stormwater on pavement skid resistance, hydroplaning, highway shoulder, sustainable highway stormwater management, and effect of stormwater and wet pavement on road safety.

II. LITERATURE REVIEW

ENVIRONMENTAL POLLUTION ASSOCIATED WITH HIGHWAY STORMWATER

Stormwater that falls on soil surfaces can either infiltrate into soils and groundwater or become soil surface runoff into streams, lakes or rivers. According to the U.S. Geological Survey, urbanization has resulted in the replacement of vegetation by impervious surfaces (such as pavement) which reduce the area where infiltration to groundwater can occur, thus increasing surface runoff into streams.¹

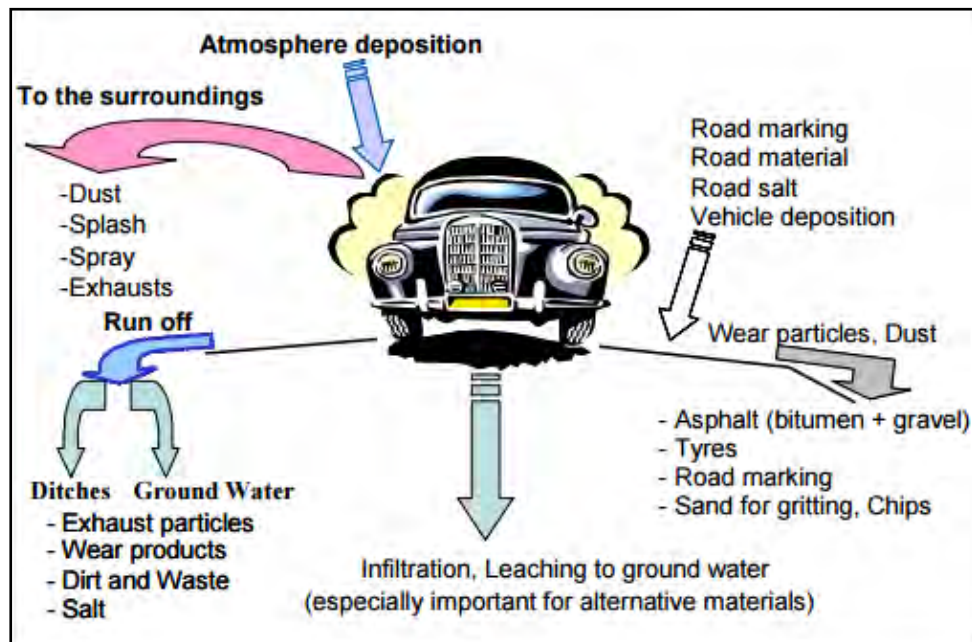
Vehicles have been noted as a source of stormwater pollution. Motor vehicles are known to deposit various pollutants on roads and parking lots, such as chemicals that are present in automobile lubrication oils, gasoline, antifreeze, tire wear, particulates coming from exhaust system, and automobile braking systems. During rainfall events, these pollutants are washed from the road surface and are carried by stormwater runoff into soils, groundwater and surface water. The constituents and sources of pollutants in highway runoff as well as typical concentrations of the pollutants have been reported by the Federal Highway Administration and are presented in Tables 1 and 2.² As documented by Walsh, et al, urban stormwater runoff has become a new class of environmental flow problem.³ Figure 1 presents an illustration of various sources of contaminants in road environments, including stormwater runoffs from roads.

Table 1. Constituents and Sources of Pollutants in Highway Runoff⁴

Constituent	Sources
Particulates	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, brushing 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

Table 2. Constituents and Concentration in Highway Runoff⁵

Parameter	Concentration (mg/L)
Total Suspended Solids (TSS)	45-798
Volatile Suspended Solids (VSS)	4.3-79
Total Organic Carbon (TOC)	24-77
Chemical Oxygen Demand (COD)	14.7-272
Biochemical Oxygen Demand (BOD)	12.7-37
Nitrate+Nitrite (NO ₃ +NO ₂)	0.15-1.636
Total Kjeldahl Nitrogen (TKN)	0.335-55.0
Total Phosphorous as P	0.113-0.998
Copper (Cu)	0.022-7.033
Lead (Pb)	0.073-1.78
Zinc (Zn)	0.056-0.929
Fecal Coliform (organisms/100 ml)	50-590

**Figure 1. An Illustration of Various Sources of Contaminants in Road Environments⁶**

STORMWATER REMOVAL FROM ROAD SURFACES

Stormwater runoff is removed from road surfaces by extensive drainage systems that combine curbs, storm sewers and ditches for direct discharge into streams. Prior to modern understanding of pollutants in highway stormwater runoff that originate from transportation vehicles, the four major reasons for removing stormwater from road surfaces were to:

1. Protect pavements from water-induced damage
2. Reduce road accidents associated with splash and spray of road water

3. Reduce road accidents associated with reduced friction coefficient (skid resistance) caused by road water
4. Reduce road accidents associated with hydroplaning caused by road water

Stormwater removal from road surfaces is an integral component of highway design that is commonly achieved by engineering the road surfaces to slope to the sides with a crown at the center. The sloping surfaces allow stormwater to move away from the road surfaces to where the water is collected using a gutter at the curb or ditches. As detailed by the Virginia Department of Transportation, curb and gutters are used in urban streets.⁷ Figure 2 presents an illustration of an urban street that uses curb and gutter. Alternative ditches are used to collect stormwater from city streets as illustrated in Figure 3.⁸ In the case of divided roadways such as highways, the rainwater is also collected at the median that divides the roadway as illustrated in Figure 4.

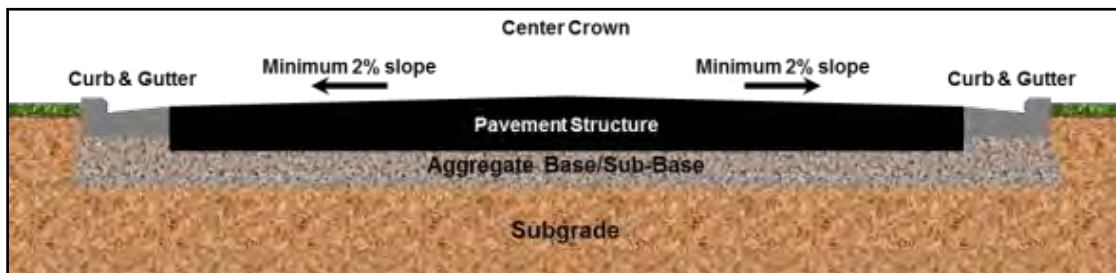


Figure 2. Cross-Section of a Two-Lane Road with Curb and Gutter for Draining of Road Runoff⁹



Figure 3. Cross-Section of a Two-Lane Road with Ditches for Draining of Road Runoff¹⁰

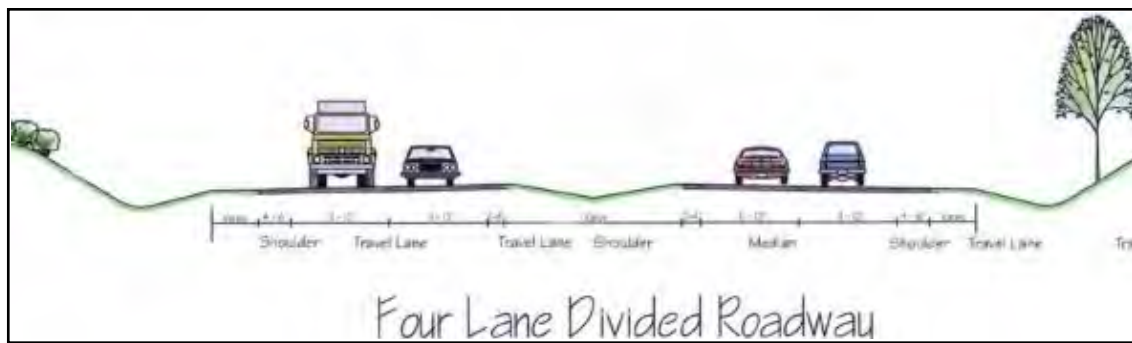


Figure 4. Cross-Section of a Four-Lane Divided Roadway for Draining of Road Runoff¹¹

HIGHWAY STORMWATER BEST MANAGEMENT PRACTICES (BMPs)

To comply with U.S. EPA requirements, transportation agencies must install stormwater BMPs to capture and treat stormwater runoff from road surface. One of the BMPs is the use of permeable (porous) pavements where stormwater moves through the pavement layers (away from the road surface). According to the U.S. Environmental Protection Agency (October 27, 2016), transportation authorities are responsible for managing stormwater runoff that discharges to the nation's waters through regulated municipal separate sewers (MS4s) along streets, roads, and highways, especially for management of stormwater runoff from highways that are solely controlled and managed by transportation authorities. For some city roads and/or county roads, the responsibility may involve multiple agencies. Table 3 presents information on the key differences between storm sewer systems (MS4s) that are solely managed by transportation authorities and those that are managed by city/county.

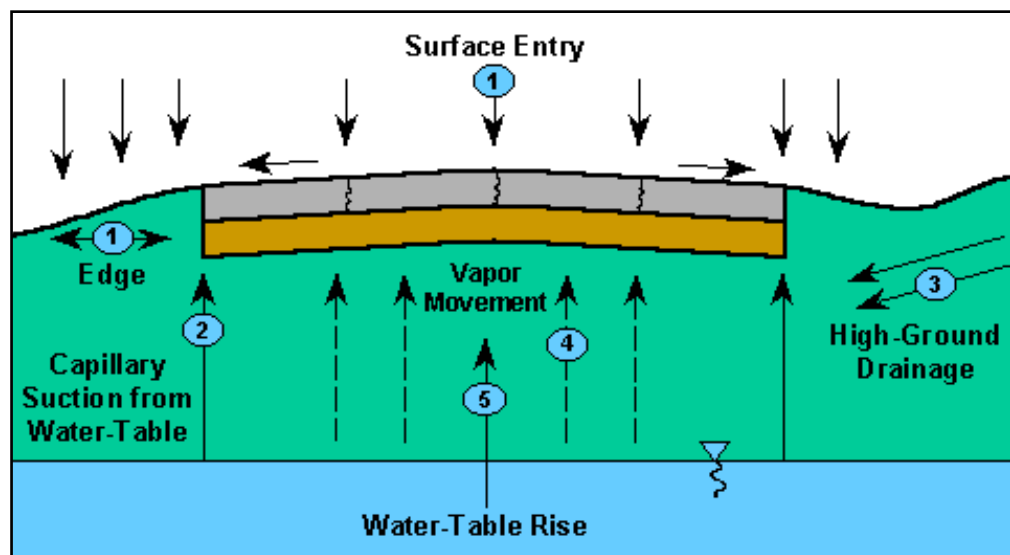
Stormwater runoff that is collected using an engineered drainage system is treated prior to discharge into streams or rivers and lakes or used to recharge groundwater by subsurface infiltration. BMPs for treating stormwater runoff have been documented by many transportation agencies, such as the U.S. Department of Transportation, the Federal Highway Administration; the California Department of Transportation; the Pennsylvania Department of Environmental Protection; the Transportation Research Board; the Texas Transportation Institute; and the California Department of Transportation.¹² This report focuses on the impact of stormwater runoff on the safe use of roadways.

Table 3. Key Differences between Transportation MS4s and Traditional (City/County) MS4s¹³

Topic	Transportation MS4	City/County MS4
Location	State transportation agencies often own streets and highways that can stretch for many miles and cross numerous waterways, watersheds, and jurisdictions.	Local governments are typically responsible for streets they own, which are usually in a limited geographical area.
Population served by MS4	State transportation agencies often serve a transient population of drivers and passengers.	Local governments often serve residents and businesses in their community boundaries.
Authorities	State transportation agencies have little to no enforcement authority to implement ordinances and must use other mechanisms.	Local government can develop and implement ordinances that they then enforce in their community boundaries.

STORMWATER IMPACT ON DURABILITY OF PAVEMENTS

Stormwater falling on road surfaces as well as subsurface water must be drained away from pavement to prevent accumulation of water in the pavement structure that can result in damage. Figure 5 presents an illustration of surface and subsurface water impact on pavement, while Table 4 shows the various mechanisms through which water enters pavements (ingresses) and exits pavements (egresses).¹⁴

**Figure 5. An Illustration of Surface and Subsurface Water Impact on Pavement¹⁵**

Water intrusion into pavement structure, including impact of subsurface moisture, is a major cause of pavement failures or damage. Reports on moisture damage to pavement have been presented by Brown, Sandy; Fwa, T.F.; Kandhall, et al; Jilie, Hu and Rendong, Guo; Pavement Interactive; Asphalt Institute; Yilmaz and Sargin; California Department of Transportation; and Suryakanta.¹⁶

Summaries of some specific common forms of distress in rigid cement or concrete pavement have been reported by Pavement Interactive (undated-1, 2006), Suryakanta (2016) and by California Department of Transportation (undated-1).¹⁷ The various types of concrete pavement defects where water is either the primary or contributing factor include (California Department of Transportation, undated-1) faulting, heave/swell, settlement, patch deterioration, scaling, pop-outs, corner cracking, intersecting cracking, pumping, joint-seal damage, punch-outs, D-cracking, Alkali-Silicate Reactivity (ASR), and freeze-thaw damage.¹⁸

Table 4. Mechanisms Through Which Water Enters (Ingresses) and Exits (Egresses) Pavements¹⁹

Ingress	Through the Pavement Surface	Through construction joint
		Through cracks due to thermal or traffic loads
		Through cracks due to pavement failure
		Penetration through intact bound layers
	From the Subgrade	By artesian head in the subgrade
		By pumping action at formation level
		By capillary action in the subgrade
	From the Road Margins	By reverse falls at formation level
		By lateral/median drain surcharging
		By capillary action in the sub-base
Egress	Through the Pavement Surface	Through cracks under pumping action
		Through the intact surfacing
	Into the Subgrade	By soak-away action
		By subgrade suction
	To the Road Margins	Into lateral/median drains under gravitational flow in the sub-base
		Into positive drains through cross drains action as collectors

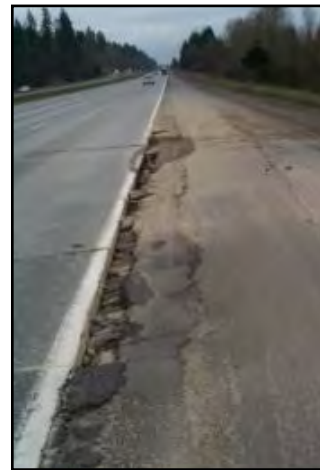
Pavement Interactive and the California Department of Transportation have presented summaries of some forms of distress in flexible (asphalt) pavements.²⁰ The various types of asphalt cement pavement defects where water (or moisture) is the responsible or contributing factor for the defects are edge cracking, overlay bumps, stripping, potholes, and pumping.

In addition, depression of asphalt pavements is reported by Pavement Interactive as a defect caused by freezing of internal moisture in the pavement.²¹ Neal also reports that upheaval (swelling) of asphalt pavement is a defect caused by expansion of the subgrade soil due to moisture or frost heave.²²

Figures 6 through 12 present pictures of some of the pavement defects that are caused by water or moisture infiltration.

Types of Water-/Moisture-Induced Pavement Failure**Sample Figure from the Source****Figure 6. Pavement Upheaval Damage²³****Figure 7. Pavement with Pothole Damage²⁴****Figure 8. Pavement Blowup Damage²⁵****Figure 9. Pavement Punch-Out Damage²⁶****Figures 6 through 9. Water-/Moisture-Induced Pavement Failures**

Types of Water-/Moisture-Induced Pavement Failure**Sample Figure from the Source**

Figure 10. Fatigue Cracking Damage²⁷**Figure 11. Pavement Pumping²⁸****Figure 12. Pumping Damage²⁹**

Figures 10 through 12. Water-/Moisture-Induced Pavement Failures

ROAD-SAFETY IMPACT OF ACCUMULATED STORMWATER ON PAVEMENT SURFACES

This section presents information on road safety issues associated with the accumulation of stormwater on pavement surfaces. The U.S. Department of Transportation, Federal Highway Administration (May 12, 2016, date of last modification) reports that weather conditions which include storm events (precipitation) and water accumulation on pavement impact road safety.³⁰ The information presented in Table 5 shows the impact of poorly managed roadway stormwater on road safety, including impact on visibility distance on the roadway, pavement friction, lane obstruction, and infrastructure damage (such as pavement damage and lane submersion).

Specifically, accumulation of stormwater on road surfaces creates conditions that reduce the safety of the traveling public due to: (1) splash and spray of road water, (2) reduced skid resistance (reduced pavement friction coefficient), and (3) hydroplaning.

Splash and Spray of Road Water

As shown in Figure 13, splash and spray of road water can significantly reduce visibility on the roadway and can result in car crashes.

Friction Coefficient (Skid Resistance) of Wet Road Surfaces

Reduced pavement friction by stormwater often results in skidding while driving on a wet road surface. Skidding can result in total loss of control of a vehicle, which may lead to an accident. According to Wilson, four factors affect skid properties of a road.³¹ The four categories of factors (pavement surface aggregate factors, load factors, environmental factors and vehicle factors) are presented in Table 6. Table 6 shows stormwater-related factors listed under environmental factors.

Various studies have shown that the friction coefficient (a measure of skid resistance) of road surfaces decreases with wet pavement surfaces.³² The impact of a rain event on the friction coefficient of road surfaces is presented in Figure 14, which shows a decreasing road friction coefficient during a rain event and an increasing friction coefficient as the road surface starts to dry. Figure 15 presents an example of road signs used by transportation agencies to warn the public about potential skidding and/or sliding.

Table 5. Weather Impacts on Roads Including Traffic and Operational Decisions³³

Road Weather Variables	Roadway Impacts	Traffic Flow Impacts	Operational Impacts
Air Temperature and Humidity	N/A	N/A	Road Treatment Strategy (e.g. snow and ice control) Construction Planning (e.g. paving and striping)
Wind Speed	Visibility Distance (due to blowing snow, dust)	Traffic Speed	Vehicle Performance (e.g. stability)
	Lane Obstruction (due to wind-blown snow, debris)	Travel Time Delay	Access Control (e.g. restrict vehicle type, close road)
		Accident Risk	Evacuation Decision Support
Precipitation (type, rate, start/end times)	Visibility Distance	Roadway Capacity	Vehicle Performance (e.g. traction)
	Pavement Friction	Traffic Speed	Driver Capabilities/Behavior
	Lane Obstruction	Traffic Time Delay	Road Treatment Strategy
		Accident Risk	Traffic Signal Timing
			Speed Limit Control
			Evacuation Decision Support
			Institutional Coordination
Fog	Visibility Distance	Traffic Speed	Driver Capabilities/Behavior
		Speed Variance	Road Treatment Strategy
		Travel Time Delay	Access Control
		Accident Risk	Speed Limit Control
Pavement Temperature	Infrastructure Damage	N/A	Road Treatment Strategy
Pavement Condition	Pavement Friction	Roadway Capacity	Vehicle Performance
	Infrastructure Damage	Traffic Speed	Driver Capabilities/Behavior (e.g. route choice)
		Travel Time Delay	Road Treatment Strategy
		Accident Risk	Traffic Signal Timing
			Speed Limit Control
Water Level	Lane Submersion	Traffic Speed	Access Control
		Travel Time Delay	Evacuation Decision Support
		Accident Risk	Institutional Coordination



Figure 13. Splash and Spray of Road Water³⁴

Table 6. Factors Affecting the Skid Properties of a Road³⁵

Pavement Surface Aggregate Factors	Load Factors	Environmental Factors	Vehicle Factors
Geological properties of the surfacing aggregate	Age of the surface	Water film thickness and drainage conditions	Vehicle speed
Surface texture (microtexture and macrotexture)	Traffic intensity and composition – equivalent vehicle loading	Surface contamination	Angle of the tire to the direction of the moving vehicle
Chip size and shape	Road geometry	Temperature	The wheel-slip ratio
Types of surfacing (concrete, asphalt mix and mix design, chip seal surface and design method)	Traffic flow conditions – congestion or free-flowing		Tire characteristics (structural type, hardness and wear)
		Rainfall	Tire tread depth and pattern

Figure Title

Figures

Figure 14. Relationship Between Friction Coefficient of Road Surface and Time of Storm Event³⁶

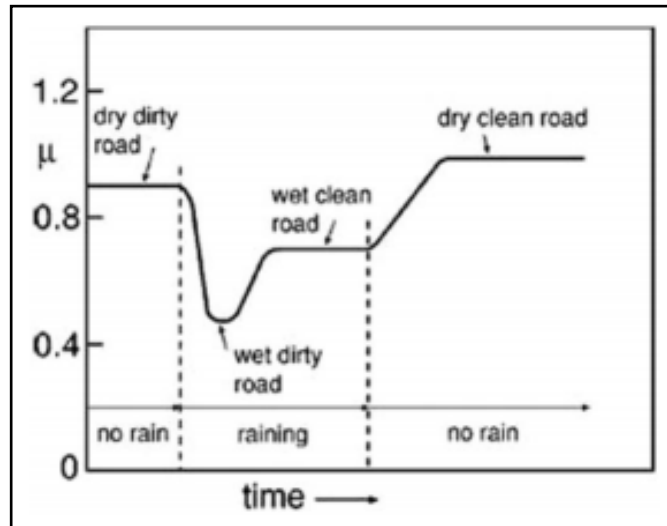


Figure 15. An Example of Road Signs About Potential Skidding, Sliding or Hydroplaning Hazard³⁷



Figures 14 and 15. (See Title in Column One)

Hydroplaning Due to Accumulated Stormwater on Road Surfaces

Hydroplaning is a phenomenon where vehicle tires lose contact with the pavement surface due to accumulated stormwater on the road pavement. Glennon reported water depth on pavement surfaces and sensitivity to water depth as the two major parameters that control hydroplaning on wet pavement surfaces as summarized in Table 7.³⁸ Table 8 presents suggested critical water depth on road pavements based on vehicle speed, showing decreasing critical water depth at higher vehicle speeds.

Table 7. Factors that Affect Hydroplaning³⁹

Water Depth		Sensitivity to Water Depth	
Roadway Factors	Environmental Factors	Driver Factors	Vehicle Factors
Compacted wheel ruts	Rainfall intensity Rainfall duration	Speed	Tire-tread wear
Pavement micro-texture		Acceleration	Tire pressure
Pavement macro-texture		Braking	Vehicle type
Pavement cross-slope		Steering	
Roadway grade			
Width of pavement			
Roadway curvature			
Longitudinal depressions			

Table 8. Suggested Hydroplaning Critical Water Depth for Various Vehicle Speed⁴⁰

Speed (mph)	Critical Water Depth (inches)
greater than 50	0.05
45-50	0.10
Less than 45	0.20

Impact of Pavement Defect (Rutting) On Hydroplaning

Rutting of pavement is the presence of depression in the wheel-tracks of roadways. Pavement rutting occurs more frequently on the surface of flexible (asphalt) pavement, which promotes accumulation of stormwater on wheel-tracks of roadways, increasing hydroplaning on roads. Figures 16 and 17 present roadways with depression in the wheel-tracks. Accumulation of water in the wheel-tracks of rutted pavement is illustrated in Figures 18 and 19. Figure 15 shows standing water on the wheel-track of the rutted pavement in comparison to the relatively dry pavement surface surrounding the rutted wheel-track.

Critical wheel-rut depth associated with pavement cross-slope for selected critical water depth at various vehicle speeds is reported by Glennon and is presented in Table 9.⁴¹ The data in Table 9 show lower critical wheel-rut depth at the same value of pavement cross-slope for the associated increasing vehicle speed with required reduced critical water depth.

Table 9. Critical Wheel-Rut Depth with Associated Critical Water Depth and Pavement Cross-Slopes for Various Vehicle Speeds⁴²

Speed (mph)	Critical Water Depth (inches)	Pavement Cross Slope (in/in)	Critical Wheel-Rut Depth (Inches)
Greater than 50	0.05	0.005	0.14
		0.010	0.23
		0.015	0.32
		0.020	0.41
		0.025	0.50

Speed (mph)	Critical Water Depth (inches)	Pavement Cross Slope (in/in)	Critical Wheel-Rut Depth (Inches)
45-50	0.10	0.005	0.19
		0.010	0.28
		0.015	0.37
		0.020	0.46
		0.025	0.55
Less than 45	0.20	0.005	0.29
		0.010	0.38
		0.015	0.47
		0.020	0.56
		0.025	0.65

Figure Title

Figure (Photo) from Source

Figure 16. Rutted Pavement Surface Showing Depression on the Wheel-Tracks⁴³




Figure 17. Rutted Japanese Pavement Surface Showing Depression on the Wheel-Tracks⁴⁴



Figure 18. Standing Water on the Wheel-Track of the Rutted Pavement⁴⁵



Figure Title	Figure (Photo) from Source
Figure 19. Stormwater Retention on Wheel-Track of Rutted Pavement⁴⁶	

Figures 16 through 19 (See Titles)

Wet Pavement Accident Statistics

Average weather-related crash statistics for a ten-year period (2005-2014) reported by the U.S. Department of Transportation, Federal Highway Administration and presented in Table 10 show about 1,258,978 weather-related crashes each year between 2005 and 2014.⁴⁷ Weather-related crashes are defined as those crashes that occur in adverse weather (i.e., rain, sleet, snow, fog, severe crosswinds, or blowing snow/sand/debris) or on slick pavement (i.e., wet pavement, snowy/slushy pavement, or icy pavement). Table 10 also shows that about 5,897 people were killed, while 445,303 people were injured in highway weather related accidents each year between 2005 and 2014. According to the report (U.S. Department of Transportation, Federal Highway Administration, 2016), the vast majority of most weather-related crashes happen on wet pavement and during rainfall.⁴⁸

Table 10. Weather Impacts on Road Safety: Weather-Related Annual Average Crash Statistics⁴⁹

	Weather-Related Crash Statistics	
	10-Year Average (2005-2014)	10-Year Percent
Weather-Related* Crashes, Injuries, and Fatalities	1,258,978 crashes	22% of vehicle crashes
	445,303 persons injured	19% of crash injuries
	5,897 persons killed	16% of crash fatalities

* "Weather-Related" crashes are those that occur in the presence of adverse weather and/or slick pavement conditions.

TYPES OF PERMEABLE PAVEMENTS USED IN HIGHWAY STORMWATER MANAGEMENT

Permeable pavement has been used to reduce imperviousness of paved surfaces. Permeable pavement helps reduce stormwater runoff by increasing stormwater infiltration. The general characteristic of all permeable pavements is that they contain pores (voids) or openings through which water passes into the soil underneath or into a drainage layer where the water is collected by piping. Permeable pavements are reported to be mainly

used for walkways, sidewalks, driveways, parking areas, parking lots, alleys, courtyards, pedestrian plazas, low-speed roads and low-speed-road shoulders. The three types of permeable pavement are:

1. Pavers
 - a. Interlocking Concrete Pavers
 - b. Brick Pavers
 - c. Stone Pavers
 - d. Grass/Turf Pavers
 - e. Grid Concrete Pavers
 - f. Grid Plastic Pavers
2. Pervious Concrete (PC)
3. Porous Asphalt (PA)⁵⁰

Pavers include concrete blocks (or stones or plastics) with voids created through open joints or corners for infiltration of stormwater. Grid pavers include concrete grid pavers (CGP) and plastic grid pavers (PGP) with openings that can be filled with gravel or grass/turf. Pervious concrete and porous asphalt are pavements with less fine materials. The reduction of fine materials helps increase void spaces in the concrete, enabling water to filter through it. According to the Minnesota Department of Natural Resources, permeable pavement is used for areas with light traffic at commercial and residential sites to replace traditional impervious surfaces of low-speed roads, alleys, parking lots, driveways, sidewalks, plazas and patios.⁵¹

The California Department of Transportation presents a table of categories of permeable pavements with examples of functions for each category (see Table 11) with a statement that categories D and E are currently not candidates for pervious pavement on Caltrans facilities.⁵²

In addition, the Virginia Department of Environmental Quality presents three design scales for permeable pavement and include that the typical application for large-scale application is limited to low-speed residential streets (see table 12).⁵³

Figures 20, 21 and 22 present pictorial information on pavers, pervious concrete and porous asphalt respectively, along with associated sample pavements. Figure 23 present a cross-sectional view of structural components of pavers, while Figure 24 presents a cross-sectional view of structural components of pervious concrete pavement and porous asphalt pavement.

As illustrated in Figure 25 (as well as in Figure 24), the need for water infiltration and storage in permeable pavements requires that there be little or no compaction of soil (subgrade). The necessary voids require that there be little or no binder fine materials. These requirements create the concern that permeable pavements are not strong enough to be used in high-volume roads and in high-speed roads. According to ConcreteNetwork.com, pervious concrete pavement has a large volume of interconnected voids of about 15 to 35 percent.⁵⁴ In a different publication, they report the required void volume in terms of void ratio stating that of 12 to 20 % is required.⁵⁵ Since void ratio controls permeability, it is the void ratio that can be used to produce pavement that possesses a required permeability and strength. Generally, low void ratio results in low permeability but higher strength of pavement. Different void ratios are also reported in Table 14 for various thicknesses of permeable friction course in different European countries and some U.S. states.

The issue of lack of strength for heavy traffic is also listed in Table 13, which presents a summary of the benefits/advantages as well as of the limitations/disadvantages of porous concrete as reported by the U.S. Department of Transportation, Federal Highway Administration.⁵⁶

Table 11. Pervious Pavement Categories⁵⁷

Category	Examples	Loading	Speed	Risk
A	Landscape area, sidewalks and bike paths (with no vehicular access), miscellaneous pavement to accept runoff from adjacent impervious areas (e.g. roofs)	No vehicular loads	N/A	Low
B	Parking lots, park & ride areas, maintenance access roads, scenic overview areas, sidewalks and bike paths (with maintenance/vehicular access), maintenance vehicle pullout	Few heavy loads	Low-speed (less than 30 mph)	Low
C	Rest areas, maintenance stations	Moderate heavy loads	Low-speed	Low
D	Shoulders, some low-volume roads, areas in front of noise barriers (beyond the traveled way)	Moderate heavy loads	High-speed	High
E	Highways, weigh stations	High heavy loads	High-speed	High


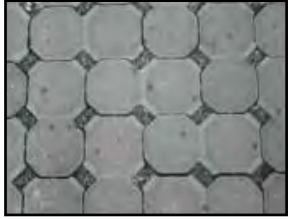
Table 12. The Three Design Scales for Permeable Pavement⁵⁸

Design Factors	Micro-Scale Pavement	Small-Scale Pavement	Large-Scale Pavement
Impervious Area Treated	250 to 1000 sq. ft.	1000 to 10,000 sq. ft.	More than 10,000 sq. ft.
Typical Applications	Driveways Walkways Court Yards Plazas Individual Sidewalks	Sidewalk Network Fire Lanes Road Shoulders Spill-Over Parking Plazas	Parking Lots with more than 40 spaces Low Speed Residential Streets
Most Suitable Pavement	IP	PA, PC, and IP	PA, PC, and IP
Load-Bearing Capacity	Foot traffic Light vehicles	Light vehicles	Heavy vehicles (moving and parked)
Reservoir Size	Infiltrate or detain some or all of the Tv	Infiltrate or detain the full Tv and as much of the CPv and design storms as possible	

Design Factors	Micro-Scale Pavement	Small-Scale Pavement	Large-Scale Pavement
External Drainage Area?	No	Yes, impervious cover up to twice the permeable pavement area may be accepted as long as sediment source controls and/or pretreatment is used	
Observation Well	No	No	Yes
Underdrain?	Rare	Depends on the soil	Back-up underdrain
Required Soil Tests	One per practice	Two per practice	One per 5,000 sq. ft. of proposed practice
Building Setbacks	Five feet down-gradient 25 feet up-gradient	Ten feet down-gradient 50 feet up-gradient	25 feet down-gradient 100 feet up-gradient

Table 13. Benefits/Advantages as well as Limitations/Disadvantages of Porous Concrete⁵⁹

Benefits/Advantages	Limitations/Disadvantages
<ol style="list-style-type: none"> 1. Effective management of stormwater runoff, which may reduce the need for curbs and the number and sizes of storm sewers 2. Reduced contamination in waterways 3. Recharging of groundwater supplies 4. More efficient land use by eliminating need for retention ponds and swales 5. Reducing heat island effect (due to evaporative cooling effect of water and convective airflow) 6. Elimination of surface ponding of water and hydroplaning potential 7. Reduced noise emissions caused by tire-pavement interaction 8. Earned LEED credit 	<ol style="list-style-type: none"> 1. Limited use in heavy vehicle traffic areas 2. Specialized construction practices 3. Extended curing time 4. Sensitive to water content and control in fresh concrete 5. Lack of standardized test methods 6. Special attention and care in design of some soil types such as expansive soils and frost-susceptible ones 7. Special attention possibly required with high groundwater

Various Types of Porous (Permeable) Pavers	Sample from Source
Interlocking Concrete Paver Parking Lot ⁶⁰	
Interlocking Concrete Paver ⁶¹	


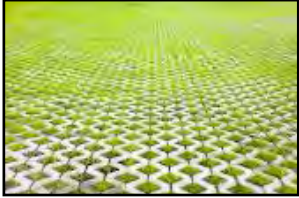




Various Types of Porous (Permeable) Pavers	Sample from Source
Grass Concrete Paver Walkway/Driveway ⁶²	
Grass Paver ⁶³	
Brick Paver ⁶⁴	

Figure 20. Examples of Various Types of Permeable Pavers

Types of Grid Pavers	Sample from Source
Concrete Grid Paver ⁶⁵	
Concrete Grid Paver Walkway ⁶⁶	
Grass Grid Paver Walkway/Driveway ⁶⁷	





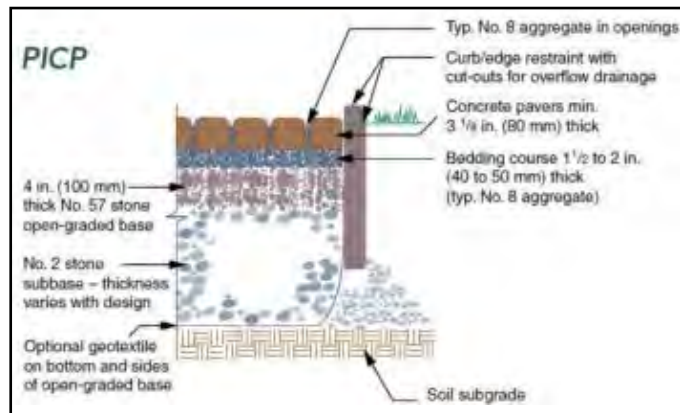
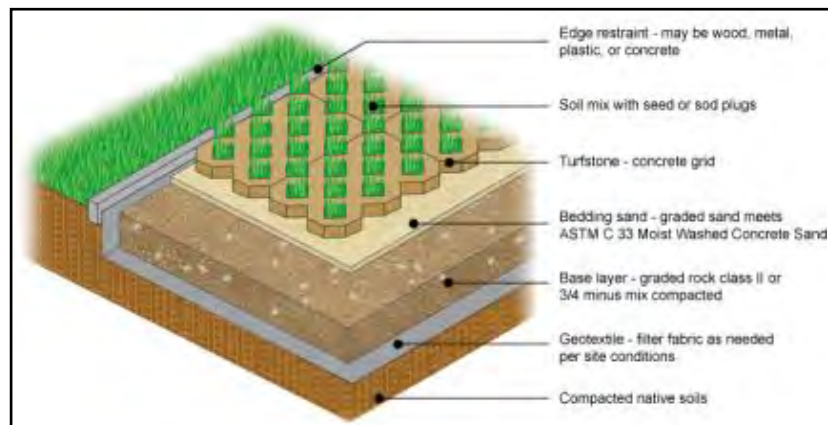
Types of Grid Pavers	Sample from Source
Plastic Grid Paver ⁶⁸	
Plastic Grid Paver Walkway/Driveway ⁶⁹	
Plastic Grid Paver Walkway ⁷⁰	

Figure 21. Examples of Various Types of Grid Permeable Pavers

Pervious Concrete and Porous Asphalt Pavement	Sample from Source
Water Draining Through a Specimen of Porous Concrete ⁷¹	
Pervious Concrete Walkway ⁷²	

Porous Asphalt Walkway⁷³Porous Asphalt Parking Lot⁷⁴

Figure 22. Examples of Pervious Concrete Pavements and Porous Asphalt Pavements

Pavers**Illustration of Cross-Sectional View of Some Permeable Pavement Structures**Interlocking Concrete Paver⁷⁵Grid Paver⁷⁶

Pavers**Illustration of Cross-Sectional View of Some Permeable Pavement Structures**

Concrete Paver with
Perforated Underdrain
Pipe⁷⁷

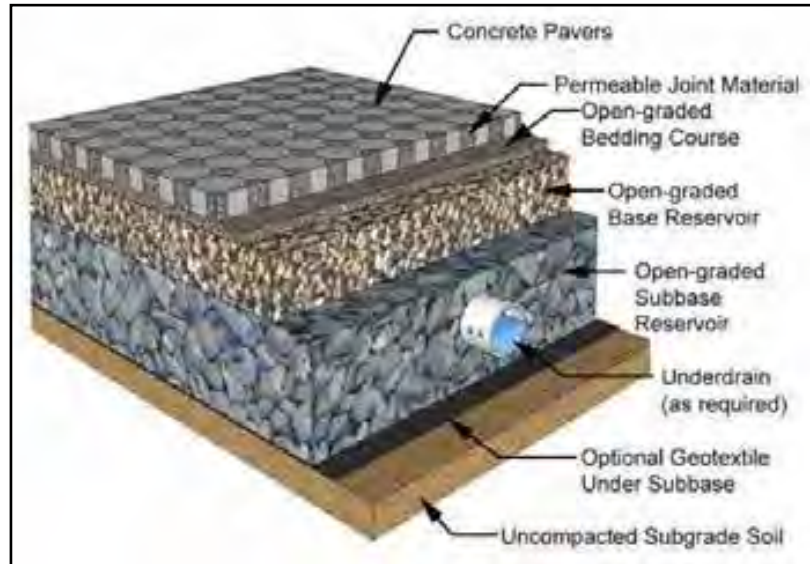
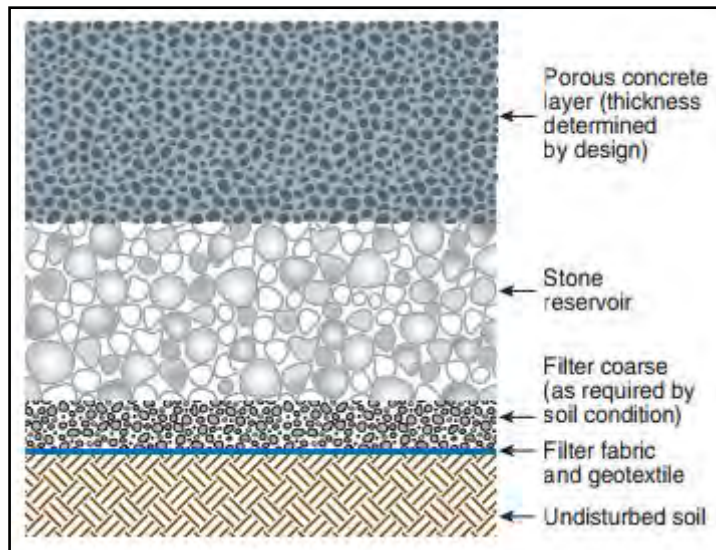
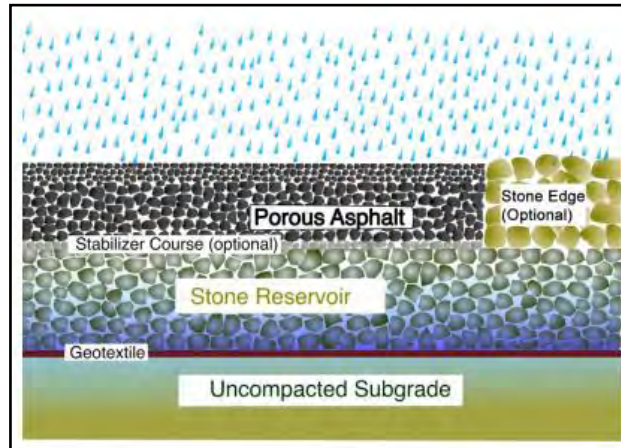


Figure 23. Illustrations of Cross-Sectional View of Structural Components of Permeable Pavers

Permeable Pavement Type**Composition of the Pavement Layers**

Pervious Concrete Pavement⁷⁸



Permeable Pavement Type**Composition of the Pavement Layers**Porous Asphalt Pavement⁷⁹

Picture Showing Loose Stone Reservoir Layer in a Permeable Pavement⁸⁰

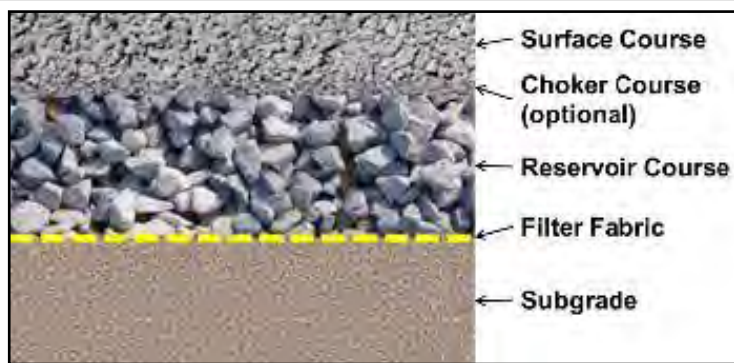
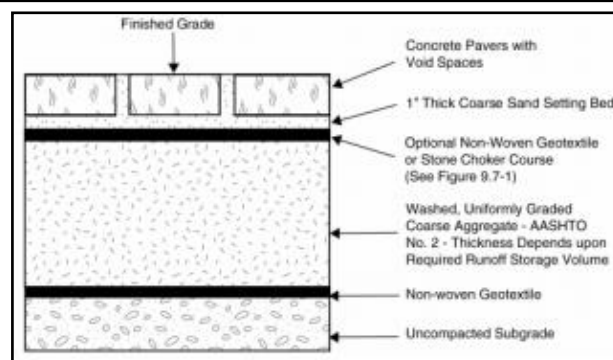


Figure 24. Illustrations of Cross-Sectional View of Structural Components of Pervious Concrete Pavement and Porous Asphalt Pavement

Permeable Paving System**Typical Details**

Permeable Pavers with Storage Base



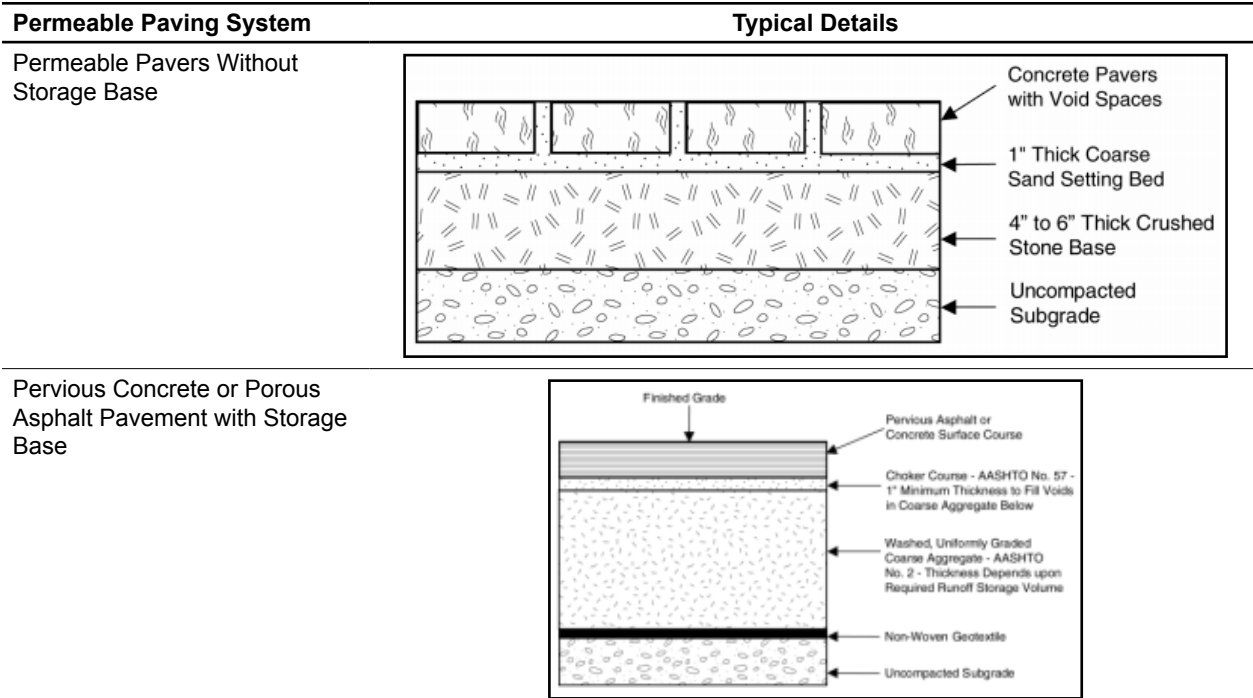


Figure 25. Typical Details of Permeable Paving System⁸¹

PERMEABLE FRICTION COURSE IN HIGHWAY STORMWATER BMPS

While full-depth permeable pavements for highways (high-volume, high-speed roads) are yet to be developed, the removal of highway stormwater by infiltration is presently achieved using permeable (or porous) friction courses (PFC), also called open-graded friction courses (OGFC). According to the National Asphalt Pavement Association, OGFC is an open-graded Hot-Mix Asphalt (HMA) mixture with interconnecting voids that provides improved surface drainage during rainfall, where the rainwater drains vertically through the OGFC to an impermeable underlying layer and then laterally to the day-lighted edge of the OGFC.⁸² The voids (air voids) are created due to the use of little fine aggregate (Pavement Interactive, 2011).⁸³

Explaining further, Ephenryecocenter.com reports that PFC is usually composed of 15- to 25-millimeter-thick hot-mix asphalt (open-graded) (HMA-O) constructed as surface overlay over an existing (or new) impervious asphalt pavement, which allows surface water to penetrate vertically within the OGFC and then move laterally towards the shoulder. There the water still needs to be collected or treated.⁸⁴

The California Department of Transportation and Stanard et al. detail many benefits of permeable friction courses (PFCs): (a) water quality benefit, (b) rain condition skid resistance, (c) noise reduction as well as reduction in hydroplaning, splash and spray, raveling, cracking, and reflective cracking.⁸⁵ In addition, the National Asphalt Pavement Association reports that the advantages gained from OGFC that drain water from road surfaces are: (a) reduced vehicle splash and spray behind vehicles, (b) enhanced visibility of pavement markings, (c) reduced nighttime surface glare in wet weather, and (d) reduced tire-pavement noise.⁸⁶

According to Stanard et al., their survey of state Departments of Transportation (state DOTs) showed that out of 47 state DOTs that responded to the survey, 17 (37%) were using PFC on a regular basis. Eight (17%) state DOTs were testing PFC by evaluating test sections over certain time periods. The remaining 21 (46%) state DOTs were not using or testing PFC at that time.⁸⁷ Figure 26 shows a map of the states for each category according to their PFC use.

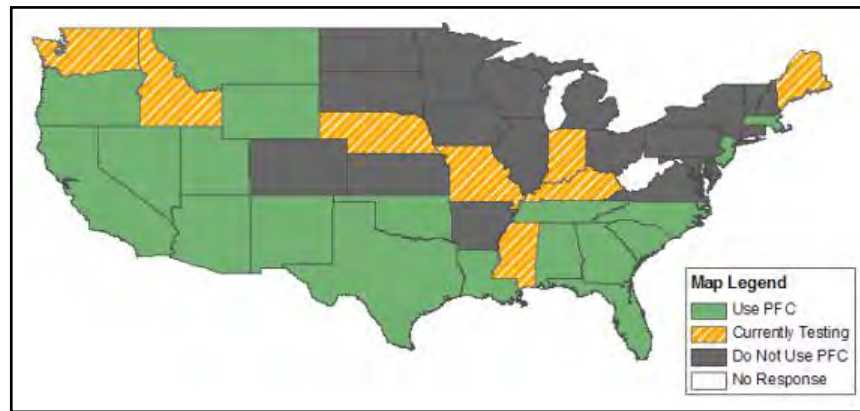


Figure 26. Survey Results of PFC Use⁸⁸

Stanard et al. also report that PFC is used in Europe. The PFC characterization data based on place of use is presented in Table 14. Stanard et al. reported on pollutant removal by PFC in comparison to conventional impervious pavement (Table 15).⁸⁹ As shown in Table 15, significant suspended solids (TSS) are removed from road stormwater by PFC. This could be a major reason for clogging problems associated with PFC, as the solids fill up the void spaces in the PFC. The mechanisms responsible for the removal of the other pollutants reported in Table 15 need some investigation. Table 15 presents information, however, on the beneficial use of permeable pavement in managing highway stormwater pollution. It shows significant reduction in pollutant concentrations in highway stormwater collected from pervious pavements in comparison to highway stormwater collected from impervious pavement. Few test reports from Texas reported in Table 15 show higher concentrations from pervious pavement, especially for low pollutant concentrations. The low pollutant concentrations might have resulted in difficult testing and analysis of the tests.

Table 14. PFC Characterization Data Based on Place of Use⁹⁰

Location	Age of Pavement	Flowrate (Q)	Hydraulic Conductivity	Void Content	Layer Thickness	Max Agg. Size
Switzerland	Initial	3.4 L/s	-	11-22%	28-50 mm	10 mm
Spain	Initial	-	-	>20%	40 mm	10 mm
Belgium	Design Spec	<1.4 L/s	-	19-25%	40 mm	
Germany	3 years	-	17-40 mm/hr.	19%	40 mm	
Netherlands	Design Spec	-	-	>20%	50 mm	11 mm
Georgia	Design Spec	-	100 m/day	10-20%	30 mm	12.5 mm
Florida	2 months		1.2 cm/s		1.4"	
Oregon	Design Spec	-	-		50 mm	19 mm
Florida	Design Spec	-	0.78 cm/s	18-22%	32 mm	10 mm

Table 15. Stormwater Pollution Control Benefit of Permeable Pavement

Location and Source	Pollutants and Concentration from Impervious and Pervious Pavements			
Netherlands ⁹¹	<i>Pollutant</i>	<i>units</i>	<i>Impervious</i>	<i>Pervious</i>
	Suspended Solids	mg/L	153 - 354	2 - 70
	Nitrogen, Kjeldahl, Total	mg/L	2 - 3	0.3 - 0.5
	Chemical Oxygen Demand	mg/L	143 - 149	16 - 18
	Chlorine	mg/L	< 1	< 1
	Copper	µg/L	91 - 163	14 - 107
	Lead	µg/L	51 - 106	2 - 22
	Zinc	µg/L	225 - 493	18 - 133
	Cadmium	µg/L	0.8 - 0.9	0.1
France ⁹²	<i>Pollutant</i>	<i>units</i>	<i>Impervious</i>	<i>Pervious</i>
	Suspended Solids	mg/L	46	8.7
	Nitrogen, Kjeldahl, Total	mg/L	2.1	1.2
	Chemical Oxygen Demand	mg/L	80	80
	NO ₃	mg/L	6.7	2.1
	Chlorine	mg/L	18	16
	Hydrocarbons, Total	mg/L	1.2	0.09
	Copper	µg/L	30	20
	Lead	µg/L	40	8.7
	Zinc	µg/L	228	77
	Cadmium	µg/L	0.88	0.28
France ⁹³	<i>Pollutant</i>	<i>units</i>	<i>Impervious</i>	<i>Pervious</i>
	Suspended Solids	mg/L	61	57
	Nitrogen, Kjeldahl, Total	mg/L	1.4	2.3
	Hydrocarbons, Total	mg/L	3.2	1.7
	Copper	µg/L	16	6
	Lead	µg/L	< 2	< 1
	Zinc	µg/L	190	63
	Cadmium	µg/L	< 0.1	< 0.1
Texas, USA ⁹⁴	Constituent	Conventional Asphalt	PFC	Reduction
	TSS (mg/L)	117.8	9.7	92
	TKN (mg/L)	1.13	0.92	19
	NO ₃ /NO ₂ (mg/l)	0.43	0.50	-16
	Total P (mg/L)	0.13	0.17	-31
	Dissolved P (mg/L)	0.06	0.09	-50
	Total Copper (µg/L)	26.8	13.1	51
	Dissolved Copper (µg/L)	5.9	10.3	-75
	Total Lead (µg/L)	12.6	<1.3	90
	Dissolved Lead (µg/L)	<1.0	<1.0	NA
	Total Zinc (µg/L)	167.4	43.2	74
	Dissolved Zinc (µg/L)	47.1	35.9	24
	COD (mg/L)	64.0	55	14

USE OF ROADWAY SHOULDERS IN STORMWATER MANAGEMENT AND SAFETY IMPLICATIONS

As previously reported, when PFC (OGFC) is used on top of impervious pavement to remove stormwater from road surfaces by infiltration, the stormwater that infiltrates the thin layer of the PFC moves laterally on top of the underlying impervious layer towards the shoulder, where it is collected and piped for treatment.

The road shoulder is defined as the portion of the roadway that is provided for emergency use by the traveling public but not for vehicular travel (see Figure 3). The issue associated with use of road shoulders for collecting stormwater that drains from traveling lanes is whether the road shoulder is structurally designed to accept the drained stormwater. Road shoulders provide many benefits to the traveling public, including a space on the roadway for emergency use to improve safety. Engineers are concerned, however, that directing stormwater from the traffic lanes to the shoulder will result in what is called a “soft shoulder,” which will create a safety hazard for vehicles that need emergency use of highway shoulders. For example, “soft shoulders” would prevent quick entrance of vehicles into the shoulder to clear the vehicle from being hit at the back.

Existing highway shoulders can be paved, partially paved or unpaved. Existing paved shoulders are typically not designed to be as “strong” as the traffic lanes (see Figure 3) and were not designed for infiltration. Figure 27 presents a picture of unpaved and partially paved highway shoulders.

Existing unpaved highway shoulders include those with just gravel on top of dirt and those that are just plain dirt or grass, which clearly shows why their safe use would be negatively impacted if they were to accept infiltration from the traffic lanes. In addition, road shoulders come in different widths, with short-width shoulders being more hazardous because of lack of space for vehicles with emergency needs to use the shoulder to quickly clear from the traffic lanes. LakeSuperiorStreams.org mentions using permeable pavements at road shoulders.⁹⁵ Shoulders with permeable pavements could provide better road safety than unpaved shoulders, but this requires research investigation. There is a need to study the types of highway shoulders that are appropriate for receiving stormwater from highway lanes underneath the shoulders in a way that would allow the road shoulder to continue to provide its intended safety functions.

Type of Shoulder**Unpaved and Partially Paved Highway Shoulders**

Unpaved Highway Shoulder⁹⁶Partially Paved Highway
Shoulder⁹⁷

Figure 27. A Picture of Unpaved and Partially Paved Highway Shoulders

III. CONCLUSIONS AND RECOMMENDATIONS

The authors reviewed the literature to produce detailed information on the effect of stormwater on the safe use of highways. In addition, the information includes data on the use of permeable pavement as one of the best management practices (BMPs) for roads and highway stormwater.

Based on the literature reviewed, the authors provide the following summary of the findings in the hope that they will help provide information on the use of permeable pavement for managing highway stormwater in a way that is safe for the traveling public.

Conclusions:

Issues with accumulation of stormwater on road surfaces:

1. Accumulation of stormwater on road surfaces results in various forms of pavement damage, reduces skid resistance (friction coefficient) of pavements, causes hydroplaning, and results in splash and spray of road water, all of which lead to car crashes, injuries and fatalities.
2. Draining of stormwater from pavement surfaces is critical for pavement durability as well as for the provision of dry pavement surfaces with associated skid resistance for the safety of the traveling public.

Types of permeable pavement:

1. There are three major types of permeable pavement: (a) permeable pavers, (b) pervious concrete pavements, and (c) porous asphalt pavements.
2. Permeable pavers include: (a) interlocking concrete pavers, (b) brick pavers, (c) stone pavers, (d) Grass/turf pavers, (e) grid concrete pavers, and (f) grid plastic pavers.
3. There is no consistency in the literature on the use of the words “pavers”, “pervious”, and “porous.” This confusion is caused by the fact that permeable pavement includes different types of pavers as well as pervious concrete pavements and porous asphalt pavements, and the terms “permeable”, “pervious” and “porous” all refer to a material with openings that allows the passage of other substances (in this case, water.)

Suitable application of permeable pavement:

1. Pavers are limited to areas with light traffic such as walkways, driveways, parking lots, parking areas, alleys, patios, courtyards, and pedestrian plazas.
2. Permeable concrete and permeable asphalt have been used for low-speed and light-traffic pavement.

3. Porous Friction Course (PFC), also known as Open-Graded Friction Course (OGFC), is a thin layer of porous Hot-Mix Asphalt (HMA) surface overlay placed on top of impervious pavement where stormwater infiltrates the thin layer of the PFC and moves laterally on top of the impervious layer toward the road shoulder, where it is collected and piped for treatment.
4. Permeable pavements have been recommended for use for road shoulders.

Benefits of using permeable pavement in roadway stormwater management:

1. Permeable pavements provide sustainable BMP for roadway stormwater by allowing roadway stormwater to infiltrate and self-drain into the pavement, where it can either flow into the underlying soil or get collected for treatment.
2. Permeable pavement also reduces the concentration of pollutants in the water that passes through its structural layers and reduces noise that results from the interaction of vehicle tires and pervious surfaces.
3. By removing water from road surfaces, permeable pavement provides safety to the traveling public.

Recommendations:

Naming of permeable pavement

1. It is common to find the different pavers as well as pervious concrete and porous asphalt being referred to as permeable pavement in the literature. To eliminate or reduce confusion, the authors recommend the following: (1) permeable pavers or pervious pavers or porous pavers, (2) permeable concrete or pervious concrete or porous concrete, and (3) permeable asphalt, or pervious asphalt or porous asphalt.

Research needs:

1. The mechanisms responsible for the removal of pollutants by permeable pavement as well as long-term pollution removal and a need for replacement of layer materials due to clogging by suspended solids should be investigated.
2. There is a need to research the types of highway shoulders that are being used for collecting stormwater from highway PFC lanes that would allow the road shoulder to continue to provide its intended safety functions.
3. There is a need to investigate appropriate permeable pavements that have the required structural strength to serve as highway shoulder to provide its intended safety functions.
4. There is a need to investigate the impact of stormwater infiltration on the stability of road side-slopes and safe use of road clear recovery zone (CRZ).

5. There is a need for test data on effect of compaction on the strength (stability) and infiltration of permeable shoulders and road side-slopes.
6. There is a need for test data on the impact of stabilization on the strength (stability) and infiltration of permeable shoulders and road side-slopes.

ABBREVIATIONS AND ACRONYMS

BOD	Biochemical Oxygen Demand
BMPs	Best Management Practices
CGP	Concrete Grid Pavers
COD	Chemical Oxygen Demand
CRZ	Clear Recovery Zone
Cu	Copper
DOTs	Departments of Transportation
HMA	Hot-Mix Asphalt
HMA-O	Hot-Mix Asphalt (open-graded)
MS4s	Municipal Separate Storm Sewer Systems
NO ₂	Nitrite
NO ₃	Nitrate
NPDES	National Pollution Discharge Elimination Standard
OGFC	Open-Graded Friction Course
P	Phosphorus
PA	Porous Asphalt
Pb	Lead
PC	Pervious Concrete
PFC	Porous (or Permeable) Friction Course
PGP	Plastic Grid Pavers
PP	Permeable Pavers
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
U.S. EPA	United States Environmental Protection Agency
VSS	Volatile Suspended Solids
Zn	Zinc

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United States House of Representatives

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