The SuDS Manual

ciria

Department
for Environment
Food & Rural Affairs

Flood and Coastal Erosion Risk Management R&D

Chapter 20

Pervious pavements

This chapter provides guidance on the design of pervious pavements – pavements that are suitable for pedestrian and/or vehicular traffic, while allowing rainwater to infiltrate through the surface and into underlying structural and foundation layers.

- ▶ *Appendix C, Section C.5.1 demonstrates how to design an infiltrating pervious pavement for a residential area.*
- ▶ *Appendix C, Section C.5.3 demonstrates how to design a lined pervious pavement for a supermarket.*

20.1 GENERAL DESCRIPTION

Pervious pavements provide a pavement suitable for pedestrian and/or vehicular traffic, while allowing rainwater to infiltrate through the surface and into the underlying structural layers. The water is temporarily stored beneath the overlying surface before use, infiltration to the ground, or controlled discharge downstream (**Section 20.1.9**).

Pervious surfaces, together with their associated substructures, are an efficient means of managing surface water runoff close to its source – intercepting runoff, reducing the volume and frequency of runoff, and providing a treatment medium. Treatment processes that occur within the surface structure, the subsurface matrix (including soil layers where infiltration is allowed) and the geotextile layers include:

- filtration
- adsorption
- biodegradation
- sedimentation.

There are two types of pervious pavements that are defined on the basis of the surfacing materials:

Porous pavements infiltrate water across their entire surface material, for example reinforced grass or gravel surfaces, resin bound gravel, porous concrete and porous asphalt.

Permeable pavements have a surface that is formed of material that is itself impervious to water. The materials are laid to provide void space through the surface to the sub-base (eg standard concrete block paving is specifically designed to allow rainwater falling onto the surface or runoff discharged over the surface to infiltrate through the joints or voids between the blocks into the underlying pavement structure).

The main types of surfaces used as part of pervious pavement construction are:

- modular permeable paving
- porous asphalt
- grass reinforcement
- resin bound gravel
- porous concrete

- macro pervious
- sports surfaces
- block porous paving.

These are summarised in **Sections 20.1.1 and 20.1.8.**

20.1.1 Modular permeable paving

The most common surface is concrete block permeable paving, but other modular surfacing materials can also be used (clay pavers, natural stone etc).

All types of surface have widened joints filled with grit to allow water into the underlying bedding layer and sub-base.

Potential uses include:

- pedestrian areas
- private driveways
- car parks
- lightly to heavily trafficked roads
- ports.

The common layout is to use modular permeable pavement for car park spaces and normal asphalt lanes between (**Figure 20.1**). This is to reduce costs and also because the asphalt can tolerate turning forces more effectively. The sub-base storage layer extends below the asphalt.

There are also spacer systems available that allow the use of normal paving slabs as permeable surfaces (with appropriate free draining joint, bedding and sub-base material). These are best suited to areas with only pedestrian traffic.

Figure 20.1 Park and ride scheme on the outskirts of Cambridge using concrete block permeable paving (courtesy EPG Limited)

Figure 20.2 Private driveway using natural stone as permeable paving (courtesy The Ethical Stone Company/ SteinTec)

20.1.2 Porous asphalt

Porous asphalt can be used as an independent surface or to provide a stronger base to concrete block permeable pavements where it is to be trafficked frequently by trucks. Porous asphalt surfacing reduces traffic noise.

Potential uses include:

- car parks
- private driveways
- lightly trafficked roads
- playgrounds
- schools.

Figure 20.3 shows porous asphalt surfacing being used for a car park at East Midlands Airport. The storage below the car park has been increased using 150 mm thick geocellular sub-base replacement units that comply with BS 7533-13:2009.

Figure 20.3 Car park at East Midlands Airport with porous asphalt surfacing (courtesy EPG Limited)

20.1.3 Grass reinforcement

Grass reinforcement uses plastic or concrete grids infilled with grass or gravel.

This type of pavement is most suitable for lightly trafficked locations, especially where it only has seasonal use, so that the grass has time to recover.

Potential uses include:

- overflow car parks to leisure facilities
- schools
- private driveways
- hotel and office car parks
- fire access or other infrequent HGV traffic.

It is important that these systems are well constructed to ensure that the soils are not compacted. The type of grass needs to suit the local climate.

Figures 20.4 and 20.5 provide examples of plastic grids and concrete grids respectively.

Figure 20.4 Plastic grids at Lake Garda, Italy (courtesy EPG Limited)

Figure 20.5 Concrete grids in a park and ride overflow car park, Gwynedd (courtesy EPG Limited)

20.1.4 Resin bound gravel

Resin bound gravel provides a wide range of finish colours, which makes it attractive for use in public, recreational spaces (**Figure 20.6**).

This type of pavement is most suitable for lightly trafficked locations.

Potential uses include:

- schools
- pedestrian areas around buildings or precincts
- private driveways.

Figure 20.6 Construction of pavement using resin bound post consumer recycled glass aggregate (courtesy Filterpave Limited)

Figure 20.7 Retail development car park with porous concrete, High Wycombe (courtesy EPG Limited)

20.1.5 Porous concrete

Porous concrete can be used as a surfacing material or to provide improved structural stability to the base of concrete block permeable pavements where it is to be trafficked frequently by trucks.

Potential uses include:

- car parks
- lightly trafficked roads.

Figure 20.7 shows a large (2800 m^2) parking area constructed with porous concrete to meet the sustainable drainage planning requirements for a new retail development site. The porous concrete surface has been used in the parking bays, traffic aisles and the access route into this area of parking. In other parts of the site it has been used only in parking bays with the impermeable asphalt aisles draining onto the porous concrete.

20.1.6 Macro pervious paving

Macro pervious systems are where normally impermeable surfaces are drained to channels or other collection systems designed to trap oil and silt.

This approach allows water storage in the sub-base below impermeable surfaces in areas where there are high traffic loads and/or high shear forces from turning vehicles (Chaddock and Nunn, 2010).

The example of a macro pervious pavement shown in **Figures 20.8 and 20.9** uses a treatment channel to collect runoff, and this discharges to an open-graded blanket of sub-base (the same materials as used below concrete block permeable paving) or geocellular sub-base replacement below the impermeable surfacing. Other options for discharge to the drainage layer could be considered such as via a bioretention system. Whatever approach is used, the main requirement is that robust treatment and removal of silt is required before discharge into the sub-base.

This type of paving serve for all types of uses, as long as the site is not subject to very high silt loads and where regular maintenance can be assured.

Figure 20.8 Macro pervious pavement under construction in the Midlands – kerb drain collector/ pollution trap with connectors before placing diffusers and permeable sub-base to the left (courtesy Phil Tomlinson)

Figure 20.9 Macro pervious pavement in warehouse yard in north-west England with channel collection/ pollution trap and concrete pavement construction (courtesy EPG Limited)

20.1.7 Sports surfaces

Either aggregate sub-base or plastic sub-base replacement units can be used below turf or porous artificial surfaces to manage surface water runoff for multi-use games areas, sports pitches and play areas.

These surfaces can be used as part of a water management system where the water is stored for irrigation or other use. Some systems include passive irrigation where water is lifted up from the storage layer into the overlying surface by capillary action.

Figure 20.10 Construction of sports drainage and attenuation layer below school sports pitch in Hull (courtesy Phil Tomlinson)

Figure 20.11 Construction of attenuation and irrigation system used below equestrian surfacing (courtesy Andrew Bowen)

20.1.8 Block porous paving

Concrete (or other recycled materials such as glass) block porous paving relies on water permeating through the porous paving unit material rather than through widened joints. Experience in the UK indicates that they are much more prone to clogging than any of the other types of system, due to very small size of the voids in the surface of the paving unit. Therefore, their potential use is limited due to this risk of clogging.

20.1.9 Systems of water management

There are three principal systems of water management below the surface of pervious pavements that are described in **Figures 20.12 to 20.14**.

Type A (**Figure 20.12**) reflects a system where all the rainfall passes into the substructure (where it may be stored temporarily) from where it infiltrates into the soil beneath. Normally, there will be no discharge from the system to a sewer or watercourse. However, an emergency overflow may be required to cater for events in excess of the design event or to allow for the system becoming less efficient (ie infiltration rates reducing) over its design life.

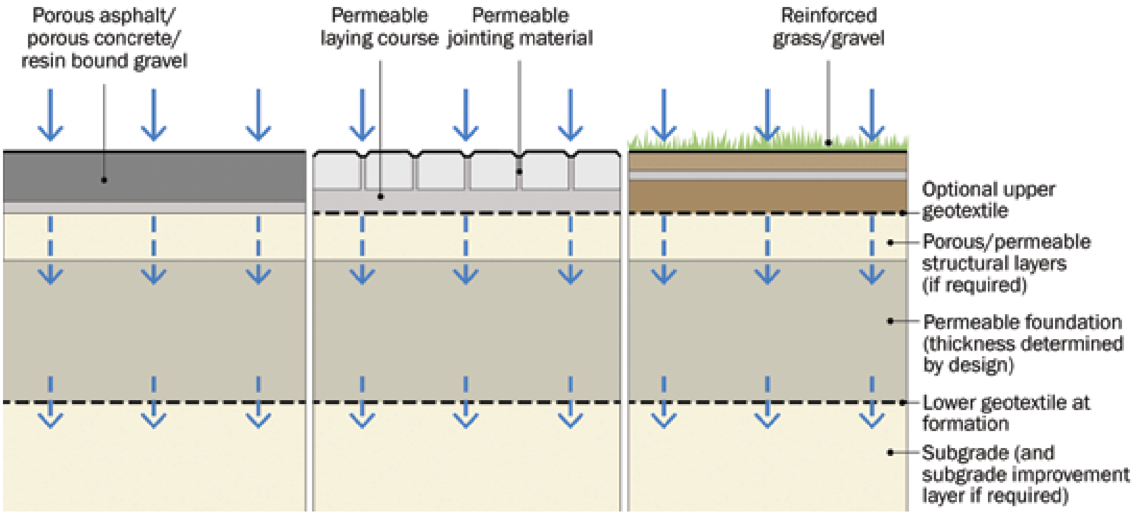


Figure 20.12 Pervious pavement system types: Type A – total infiltration

In a Type B system (**Figure 20.13**), the proportion of the rainfall that exceeds the infiltration capacity of the subsoils flows to the receiving drainage system. This can occur by direct drainage through the sub-base or by conveyance via perforated pipes within or below it. Geocomposite blankets can also be used to collect and convey water below the sub-base layer or can be placed vertically at the edges of the construction to allow connection to a pipe. By preventing the build-up of water above the subgrade, the risks to soil stability are reduced.

There is no infiltration with a Type C system (**Figure 20.14**). The system is generally wrapped in an impermeable, flexible membrane placed above the subgrade (formation level). Once the water has filtered through the sub-base, it is conveyed to the outfall via perforated pipes or fin drains. This can be used for situations where:

- soils have low permeability or low strength (and could therefore be damaged by the introduction of infiltrating water)
- the water is to be harvested and used
- the underlying groundwater is sensitive and requires protection
- the water table is within 1 m of the sub-base
- the site is contaminated and the risks of mobilising contaminants must be minimised.

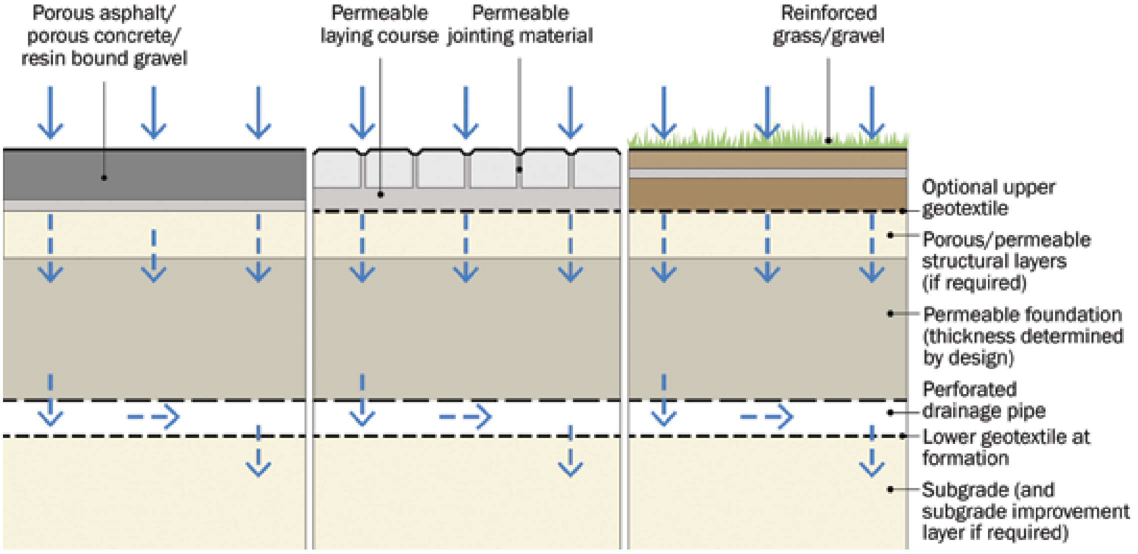


Figure 20.13 Pervious pavement system types: Type B – partial infiltration

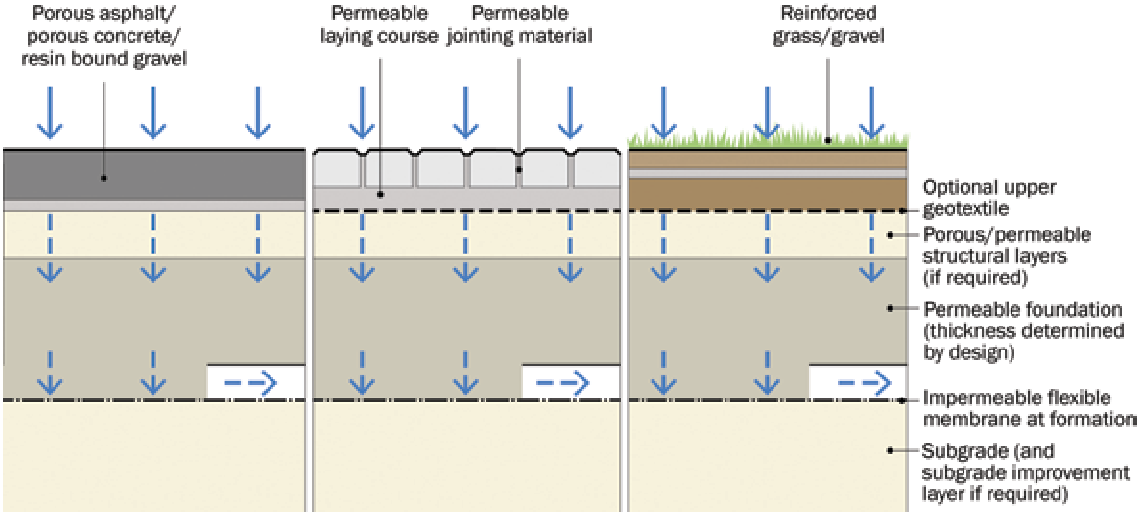


Figure 20.14 Pervious pavement system types: Type C – no infiltration

Variations of these three basic types of pervious pavement construction include the following:

- Grass reinforcement systems can be used over standard pavement materials (eg Type 1 sub-base). These systems will provide Interception, but attenuation and treatment of the residual runoff from the surface will still be required, as they do not provide for any storage of water in the sub-base.
- Impermeable asphalt or concrete surfacing used over permeable sub-base (known as macro pervious surfaces [MPPS], or reservoir pavements) where the water is introduced into the storage in the sub-base via a series of distinct entry points – fast enough to prevent flooding during the design storm but without allowing silt and debris to enter the sub-base. The system offers the opportunity to accrue the benefits of a pervious pavement when the use of traditional paving surfaces is the preferred option due to traffic considerations. The performance of the silt trapping devices is crucial in this application as it is impossible to subsequently remove silt from the sub-base without complete system reinstatement. Simple catch pits or normal channels are not suitable.

20.2 GENERAL DESIGN CONSIDERATIONS

There is a range of surfacing materials that can be used to allow water to soak into the underlying sub-base. The choice of the most appropriate surfacing for a given location is crucial to the successful use of pervious pavements to manage surface water. This will mainly be based on the expected traffic loadings and the visual appearance that is required.

Type C system (**Section 20.1.9**) designs may be modified to allow a proportion of runoff to be stored and used for various non-potable applications such as irrigation, toilet flushing etc (**Figure 20.15** and Beecham *et al*, 2010). Because of the evaporation occurring, the proportion of runoff captured by a pervious pavement system is lower than from an impermeable surface, and it is recommended that runoff coefficients of 40% are used for rainwater harvesting design (Interpave, 2010).

▶ For further information on opportunities for using rainwater, see **Chapter 11** and Leggett *et al* (2001a, 2001b).

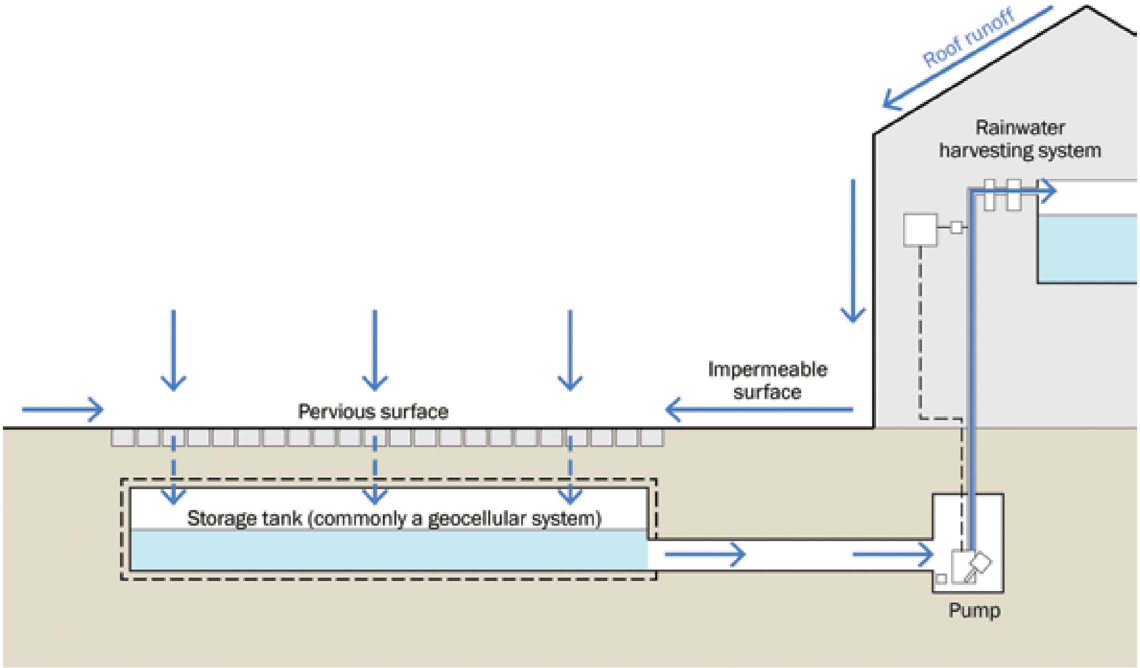


Figure 20.15 Example of rainwater harvesting system (from Interpave, 2010)

The aggregate sub-base in pervious pavements can sometimes be replaced with geocellular sub-base replacement systems (**Chapter 21**). These will provide a higher storage capacity (with > 90% porosity), but consideration will need to be given to the use of geotextile layers to ensure adequacy of treatment of the runoff (**Section 20.6**). The use of geocellular structures beneath paving systems exposes them to very high loads. Module elastic deformation and the strength of joints between modules are critical to the performance of the overlying layers of blocks or asphalt, and careful design will be required.

▶ Further advice on using geocellular structures is provided in **Chapter 21**.

Pervious pavements are generally used to manage rainfall landing directly on the surface, but their capacity is such that they are often also used to manage runoff draining from adjacent areas, such as roofs or adjacent impermeable areas of car parks. If an adjacent impermeable area is draining onto the surface of the pervious pavement, the maximum ratio should be 2:1 (impermeable:pervious) to minimise the risk of silt

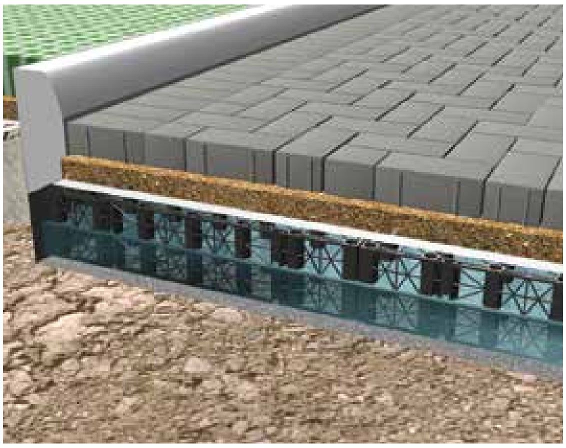


Figure 20.16 Concrete block permeable paving with geocellular sub-base replacement system (from Interpave, 2013)

completely blocking the pavement surface. Where pavements are draining adjacent impermeable areas, clogging will initially develop close to the impermeable pavement and a clogging front will gradually migrate across the pervious pavement.

Roof drainage can direct large volumes of water into the pavement very quickly, and inlet diffusers may be required to regulate the flow velocities (**Section 20.10.1**). These require very careful design, especially where syphonic drainage is discharging into the pavement. Where water from roofs is directed via catch pits directly into the sub-base the ratio of impermeable:pervious above does not apply. For smaller areas of roof it is possible to discharge the downpipe directly onto the pavement, in which case the maximum ratio of 2:1 should still apply.

▶ Health and safety risk management design guidance is presented in **Chapter 36**.

20.3 SELECTION AND SITING OF PERVIOUS PAVEMENTS

Pervious pavements can be used on most sites, but they need to be used in appropriate locations. They can often be combined with other solutions such as detention basins, ponds and wetlands allowing these subsequent attenuation and treatment features to be shallower and smaller. The use of pervious pavement should be avoided where there is a high risk of silt loads on the surface.

Pervious pavements are typically built as an alternative to impermeable surfaces and therefore require no extra development space for their construction. They require only a small head difference from the runoff surface to their outfall and can therefore be employed on very flat terrain.

Constructed pervious pavements tend to be used to drain highways with low traffic volumes and speeds (less than 30 mph), car parking areas and other lightly trafficked or non-trafficked surfaces. However, they are capable of supporting HGV traffic (Chaddock and Nunn, 2010, BS 7533-13:2009) and, in the UK, specific types of pervious pavements have been used successfully for surfaces with heavy axle load traffic. In the USA, there are isolated examples of successful use of pervious pavements on state highways, and they are currently looking at the use of pervious concrete design for heavily trafficked pavements (Wanielista and Chopra, 2007). Such pavements should be designed on an individual basis and in conjunction with manufacturers and experienced geotechnical and pavement engineers. They should have a stiff layer of asphalt, asphalt concrete, concrete or hydraulically bound coarse-graded aggregate below the bedding layer. The main concerns are the frequent vehicle braking and turning actions that can cause the surfaces to rut, concrete blocks to spread and porous asphalt to spall.

The acceptability of infiltration from a permeable pavement should be determined by following the guidance provided in **Section 25.2**, complying with all relevant requirements for infiltration systems with respect to ground stability, depth to water table etc and **Section 26.7** for the protection of groundwater.

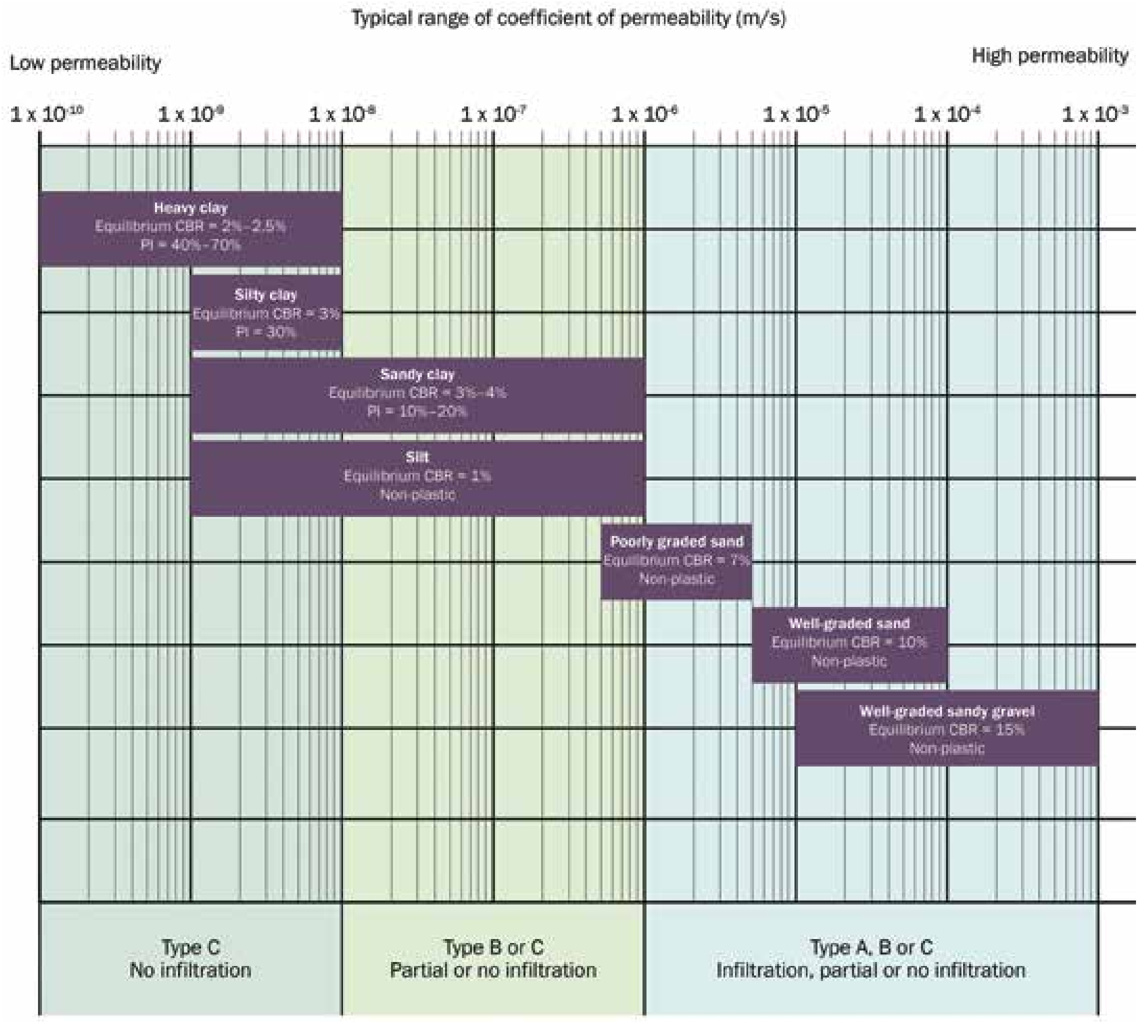
Unlined pavements should not be used on brownfield sites unless it has been demonstrated that the risk posed by leaching of contaminants is managed to acceptable levels. Unlined pavements should not be used to treat runoff from areas with high contaminant loads if the risk of groundwater pollution due to infiltration is unacceptably high. Where infiltration is prevented, the seasonally high groundwater level should always be below the base of the pavement formation.

Pervious pavements can be used in most ground conditions and can be sited on waste, uncontrolled or non-engineered fill, if necessary with a liner, where the design allows for differential settlement. Unlined pavements should not be used in locations where infiltrating water may cause slope instability or foundation problems, for example areas of landslides, at the top of cutting or embankment slopes or close to building foundations unless a full assessment of the risks has been carried out by a suitably qualified geotechnical engineer or engineering geologist.

▶ For information on allowing infiltration close to buildings, see **Chapter 25**.

The effects of water storage on the structural capacity of the underlying soils should also be carefully assessed and slopes and collection systems used to manage these risks. There should always be a nominal fall on the pavement formation level.

Figure 20.17 gives guidance on soil classification, and **Table 20.1** recommends appropriate pavement systems for a range of subgrade conditions. Both are taken from Interpave (2010), but can be applied to any surfacing system, not just concrete block permeable paving (CBPP).



Note: A significant proportion of clay and silt (> 15% of particles less than 63 μm) will reduce the permeability and CBR values of sand and of gravels

Figure 20.17 Soil classification guide (after Interpave, 2010)

The location of buried services should be taken into account in any design to ensure the long-term success of pervious pavement projects. Shallow services should, wherever possible, be located beneath areas of conventional impermeable surfacing (which drain to adjacent pervious areas), or within service corridors or verges, thus avoiding the pervious construction. Deeper surface and foul sewers can often pass below the sub-base formation layer. This approach will minimise the need to excavate through the pervious construction to access services.

Using an appropriate mix of permeable and impermeable surfacing can provide structure to the overall design layout – both visually and technically, helping designers realise aspirations promoted by DCLG (2007). For example, an impermeable central carriageway might be employed to contain services, visually differentiated from pervious parking bays. Alternatively, impermeable service crossings could also be used as pedestrian ways, clearly differentiated from pervious areas intended for vehicles.

TABLE 20.1 **Guidance on selection of a pavement system type (after Interpave, 2010)**

Ground characteristics		Type A: total infiltration	Type B: partial infiltration	Type C: no infiltration
Permeability of subgrade defined by coefficient of permeability k (m/s)	1×10^{-6} to 1×10^{-3}	✓	✓	✓
	1×10^{-8} to 1×10^{-6}	✗	✓	✓
	1×10^{-10} to 1×10^{-8}	✗	✗ (1)	✓
Highest expected water level within 1000 mm of formation level		✗	✗	✓
Pollutants present in subgrade		✗	✗	✓
Ground conditions such that infiltration of water is not recommended (solution features, old mine working etc, **Chapter 8**)		✗	✗	✓

Note

1 Partial infiltration systems may be used in soils with permeability less than 10^{-8} m/s but the infiltration of water is not allowed for in the storage design. This helps with the provision of Interception.

BOX 20.1 **Units used for infiltration**

The SI unit of reporting soil permeability is m/s. Therefore, soil infiltration rates are usually also reported in m/s. There is a general understanding within the industry of what constitutes a high or low value quoted in these units.

The infiltration rate of rainwater into the top surface of a pervious pavement is often compared to rainfall intensity. Rainfall intensity is reported in mm/h, and therefore the infiltration of water into the pervious pavement is reported in these units.

There is an extensive body of evidence demonstrating that pervious pavements perform adequately in cold climates. They tend to withstand freeze–thaw conditions well and tend to be less affected by frost heave than standard pavement surfacing (Lake County Forest Preserves, 2003; Kevern *et al,* 2009) due to the air in the aggregate base acting as an insulating layer limiting frost penetration into the pavement, coupled with the higher internal latent heat associated with the higher soil moisture content. Pervious pavements do not tend to ice on the surface because water and melting snow drain straight into the pavement rather than ponding before runoff. Pervious pavements also tend to thaw faster than normal pavements and thus require lower than average salt applications. Studies have also shown little loss in the treatment performance of pervious pavements during cold weather. However, they can develop a hoar frost on the surface more frequently than normal pavement construction.

20.4 OVERALL DESIGN REQUIREMENTS

Pervious pavements provide two functions.

1. They need to be able to effectively capture the design storm event and discharge it in a controlled manner to the subgrade or drainage system.
2. They need to provide sufficient structural resistance to withstand the loadings imposed by vehicles travelling on the surface.

Therefore there are two sets of calculations required, and the greater thickness of permeable sub-base from the two calculations is used as the design thickness. Pervious pavements generally require flow controls at the outlets to ensure effective use of the storage in the sub-base. A recommended design flowchart is provided in **Figure 20.19**.

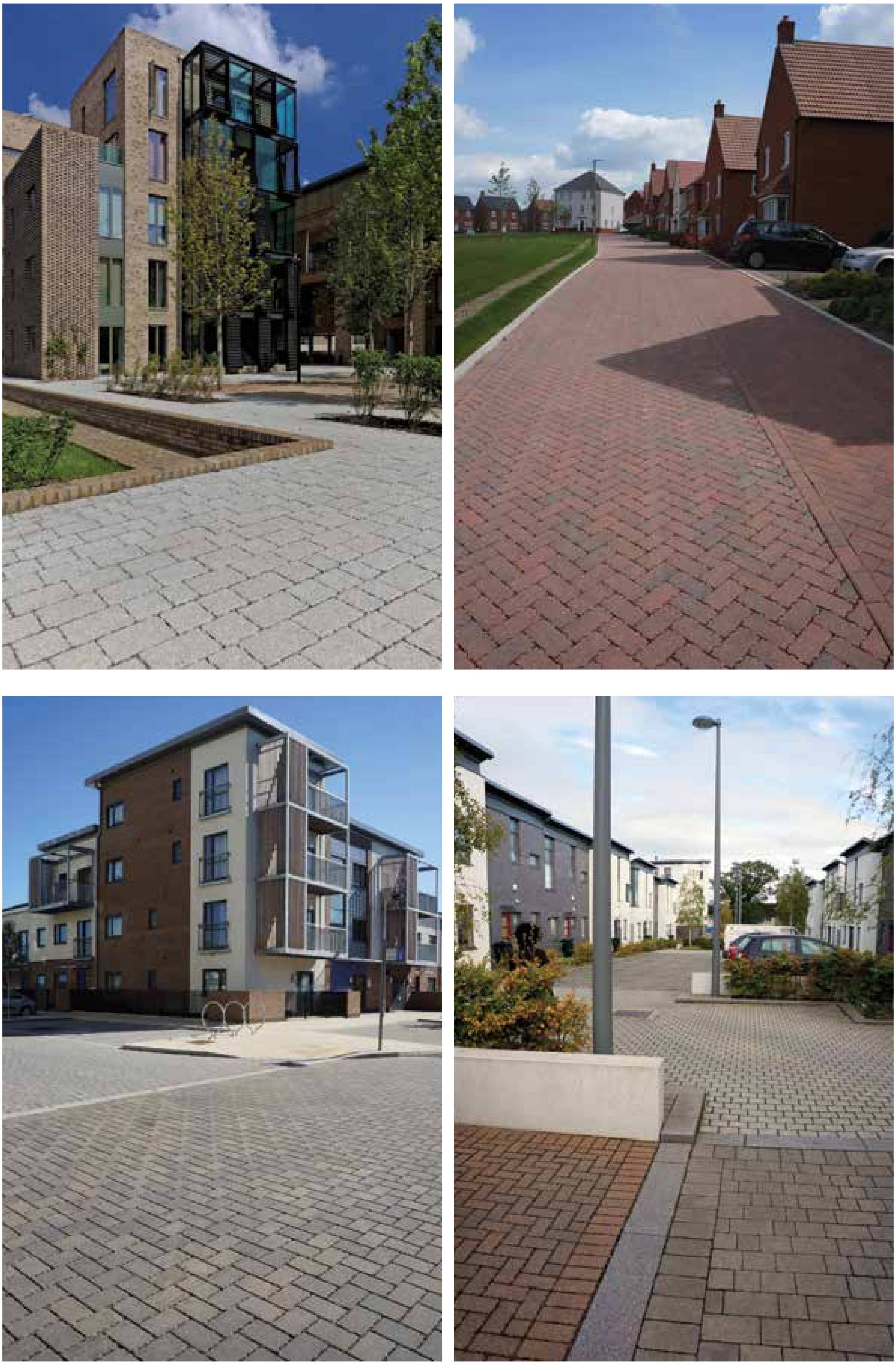


Figure 20.18 Examples of different block paving finishes (courtesy Interpave)

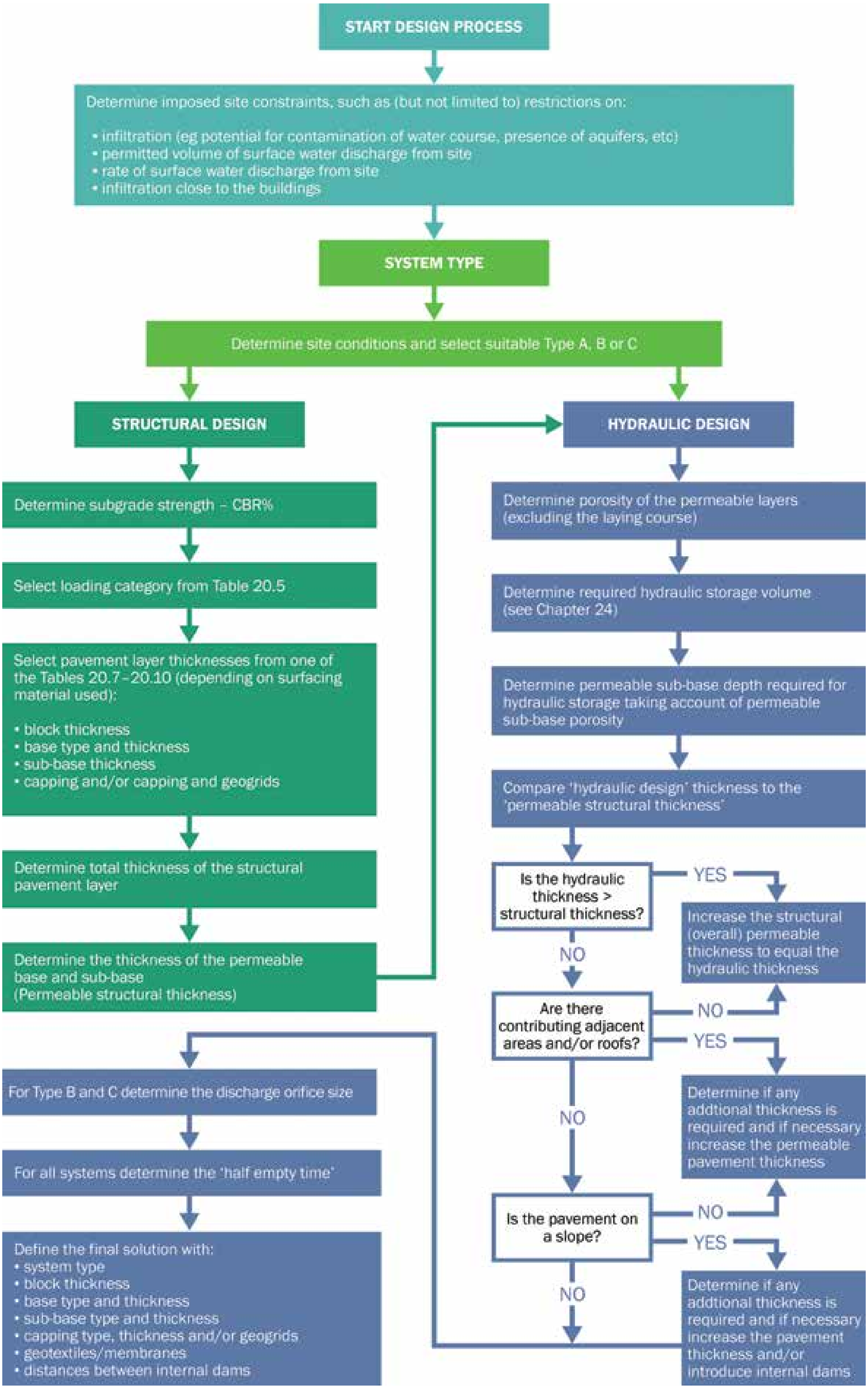


Figure 20.19 Pervious pavement design flow chart (after Interpave, 2010)

20.5 HYDRAULIC DESIGN

20.5.1 General

There are four aspects to the hydraulic design of pervious pavements:

a) confirmation of the adequacy of the rate of infiltration of rainwater through the pavement surface

b) calculation of the storage volume required for design storm event management

c) calculation of the outfall capacity required to convey and control the discharge of water from the pavement structure

d) exceedance design

Exceedance design is discussed in **Section 20.5.5**, while (a), (b) and (c) are discussed here.

a) Infiltration of rainwater through the pervious surface

The surface infiltration rate should be significantly greater than the design rainfall intensity to avoid surface water ponding, and the calculation of the inflow rate should include all anticipated runoff from adjacent areas. Typically, infiltration capacities of pervious surfaces are significantly greater than design rainfall intensities and are not generally limiting factors for the use of a pervious pavement. Surface ponding of exceedance events should be planned for in the design, taking account of the likely water depth on the surface and the time for which it is likely to remain. Note that the surface infiltration capacity has no relationship to the infiltration capacity of the soils below the pavement construction.

A minimum value of 2500 mm/h (for new pavements) is considered reasonable for a pavement surface to be considered pervious in respect of surface water management (when tested in accordance with standard test methods). The infiltration capacity of the surface materials is normally stated by the supplier or manufacturer. There is no standard UK or European test procedure for measuring the surface infiltration rate of pervious surfaces. However, ASTM C1781M-13 has been developed for concrete block permeable paving and ASTM C1701M-09 for pervious concrete (it could also be applied to other porous materials such as porous asphalt and gravel- or grass-filled reinforcement systems). It is recommended that manufacturers should provide surface infiltration rates measured using test methods and that they are adopted as a standard method in the UK with the following amendments:

1 The results should be stated in both mm/h and m/s.

2 Sealing the infiltration ring to the surface to be tested should be achieved using mastic sealant, rapid set mortar or other suitable sealant material.

There is no doubt that the rate of infiltration through porous and permeable surfaces reduces over time. The main ways that the surfaces become blocked are:

- washing of topsoil and construction materials onto the surface – these risks should be reduced through construction best practice and appropriate detailed design
- accumulation of silt and debris in the joints or pore spaces at or close to the surface
- the application of gritting sand to car park surfaces (not common practice in the UK) and the use of sand as a jointing material in concrete block permeable paving (not UK practice)
- binder slumping from the aggregate matrix in porous asphalt over time, which then drains into the voids – the risk of this occurring should be reduced by the use of modern binder technology to promote adhesion of the binder.

However, it is very rare that the clogging causes complete sealing of the whole surface, and normally it will continue to provide sufficient drainage capacity. It is recommended that a factor of safety of 10 is applied to the surface infiltration rate of all surface types, to allow for clogging to affect a proportion of the surface area over the pavement design life (ie the long-term surface infiltration rate will be a minimum of 250 mm/h). Information on rehabilitating pavements that suffer from clogging is provided in **Section 20.14**.

Despite the reduction in surface infiltration rate over time, the available evidence (**Table 20.2**) indicates that the long-term reduced rate is more than sufficient in most cases to deal with any rainfall intensities likely to occur in the UK. Even if the pavements become completely clogged, the evidence shows that they can be rehabilitated using sweepers combined with re-gritting of the joints.

Figure 20.20 shows an example of concrete block permeable paving after a 50 mm depth rainfall event. This pavement was about six years old at the time and had not been maintained in that time.

TABLE 20.2 **Evidence of durability and clogging of the surfaces of pervious pavements**

Pervious pavement type	Clogging mechanism	Evidence of likely clogging rates/extents	Rehabilitation mechanisms
Grass reinforcement (concrete grids)	Sand-filled voids with grass overgrowth act like sand filters and trap sediment close to the surface	Clogging depths of 6–12 mm (Urban Waterways, 2011); loss of 60–75% of the initial surface infiltration rate during a simulated 35-year life (Jayasuriya *et al*, 2007)	Clogged sand can be removed and replaced with mechanical sweepers, although the grass will also have to be reseeded
Porous asphalt	Dust and sediment trapped in surface pores	Clogging in the top 25–75 mm can occur rapidly without good design and maintenance, where silt loads are significant. Evidence in the UK is that pavements are still serviceable after about eight years	Rotating sweeper and jet wash; use a surface layer with finer pores (ie smaller aggregate) and increasing aggregate size with depth (Beeldens and Herrier, 2006)
Porous concrete	Dust and sediment trapped in surface pores	Clogging in the top 25–75 mm can occur rapidly without good design and maintenance, where silt loads are significant	Use a surface layer with finer pores (ie smaller aggregate) and increasing aggregate size with depth (Beeldens and Herrier, 2006); specialist rotating and oscillating sweeper (the type used to remove tyre residue from airport runways
Concrete block permeable paving	Dust and sediment is trapped in the joints between the blocks	Penetration to 50 mm (over six years) (Urban Waterways, 2011); loss of 70–90% of as-new surface infiltration rate over the first few years of use after which infiltration rate levels off and remain effectively constant (Borgwardt, 2006); in heavily trafficked pavements the wheel tracks may become completely clogged in a few years (Chaddock and Nunn, 2010)	Brushing and suction sweeping of the surface, replacement of top 20 mm of jointing material, herbicide application and weed removal programmes

b) Pavement subsurface storage capacity

The required capacity of the sub-base depends on rainfall characteristics, design return period, infiltration potential into the subgrade, discharge constraints, and the impermeable area draining to the pervious pavement.

The thickness of the sub-base required can be obtained by simple calculation (see Interpave, 2010) or by detailed hydrological and hydraulic modelling. It should be noted that the Interpave procedure assumes no time of concentration, which is likely to output a conservative design depth requirement. Proprietary drainage software now exists that can predict hydraulic profiles across a pavement and computes capacities for design events in more detail. However, many of the algorithms in the models are still very simple and only approximate to actual performance.

Figure 20.20 Concrete block permeable paving after a 50 mm rainfall event (courtesy EPG Limited)

Analysis (Kellagher, 2013) shows that typically, at least twice the area of the pavement surface can be served by the sub-base when very tight throttle controls are applied, and nearly three times the area when the throttle rate is greater than 5 l/s/ha. However, where adjacent areas drain into the surface, the ratio of impermeable to pervious should be limited to 2:1 to prevent clogging. If roof water discharges into the sub-base via catch pits, the ratio can be increased.

Where partial or total infiltration systems are used, the infiltration will mean that the system can therefore serve even greater areas. However, care should be taken not to hydraulically overload the pavement, as this can cause soil stability risks due to saturation.

Calculations for a range of rainfall durations should be carried out to verify the performance of the available storage volume.

The available storage in the base/sub-base layer is determined by the volume of the sub-base, the slope of the pavement and the usable voids (ie voids that are freely draining) within the aggregate. A commonly used value of porosity is 30% for the aggregates that meet the requirements for coarse-graded aggregates in BS 7533-13:2009 or Type 3 sub-base in accordance with DfT (1998). Care should be taken if using values higher than this, that all the voids in a material are free draining (eg clay soils may have a porosity but the voids are very small and not suitable for storing water). If a porosity greater than 30% is used in the design, the material should be tested on site to confirm compliance.

On sloping sites, the volume of available storage within the sub-base will be reduced when compared to a flat surface. ICPI (2011) suggests that where slopes are 3% or greater, designers should consider terracing or internal check dams in the sub-base to provide a series of compartments (BS 7533-13:2009) Where the water infiltrates to the soil below, this solution is easy to design, as the different compartments do not need to be interconnected with pipes.

For Type C systems, water still has to be allowed to flow out of the sub-base that is confined by the check dam into the lower compartment via a pipe or other structure. Flow can be from one compartment to another if it is possible to provide a sufficiently low flow control (very small orifices may be required). The minimum size of orifice should be 20 mm. Solutions to this issue include combining areas so that a larger flow control can be used, or discharging several dammed areas to a single larger flow control outside the permeable pavement area (if levels permit). The design of the flow control and interconnecting pipe should minimise the risk of blockage. Wherever possible, the design should allow access to either side of the flow control in case it needs to be unblocked (although the risk of this occurring is very low).

Other solutions to storage on sloping sites include terracing the site into a series of flat areas, making the formation as a series of horizontal terraces with the pavement surface sloping above them, making the sub-base thicker so that the water at the low end of the pavement remains within the sub-base or providing extra storage in a trench at the toe of a slope.

Research into the potential impact of surface slope on infiltration rates into the pavement surface has demonstrated that below slopes of approximately 20%, this should not be a significant issue. The impact of slope on storage and potential design solutions are shown in **Figure 20.21**.

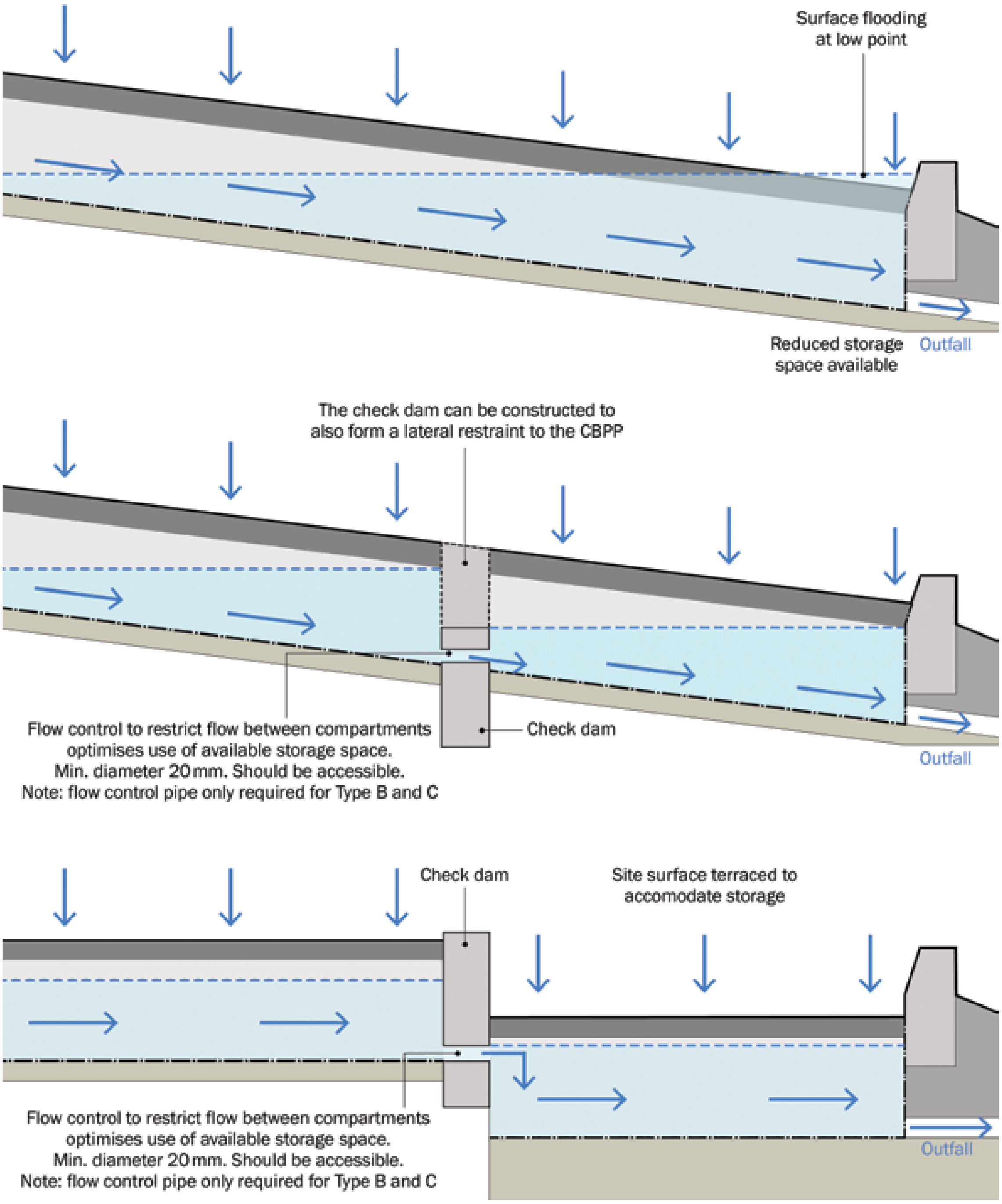


Figure 20.21 Control of water on sloping sites (from Interpave, 2013)

c) Outflow from the pavement structure

For the sub-base storage to operate effectively, the system requires flow controls (unless the only discharge mechanism is via infiltration). These are generally small orifice plates in a control chamber and can be very small (minimum 20 mm) because the risk of blockage is low, because the water has been filtered. Where the sub-base is divided into discrete areas (separated by impermeable construction), careful consideration is required of flow control locations and characteristics to ensure that the use of the storage is optimised and that there is no risk of inappropriate constriction and potential flooding. The outflow can also be to a rainwater harvesting system via a sump and pump chamber.

The spacing of the outlet pipes or collector pipes for sealed systems can be determined in an approximate manner using guidance provided by Cedergren (1974). The maximum surface runoff rate that can be removed by a flat permeable sub-base can be estimated using **Equation 20.1.**

EQ. 20.1

Equation to estimate outfall pipe spacing

$$q = k\,(h/b)^2$$

q = maximum intensity of rainfall entering into the pavement sub-base that can be drained by pipes at spacing of 2b and sub-base thickness of h (m/s)

k = coefficient of permeability of sub-base (m/s) (minimum value is specified in **Section 20.11**)

h = maximum depth of water stored in sub-base (and base if appropriate) above impermeable formation or membrane (m)

2b = distance between pipes (m)

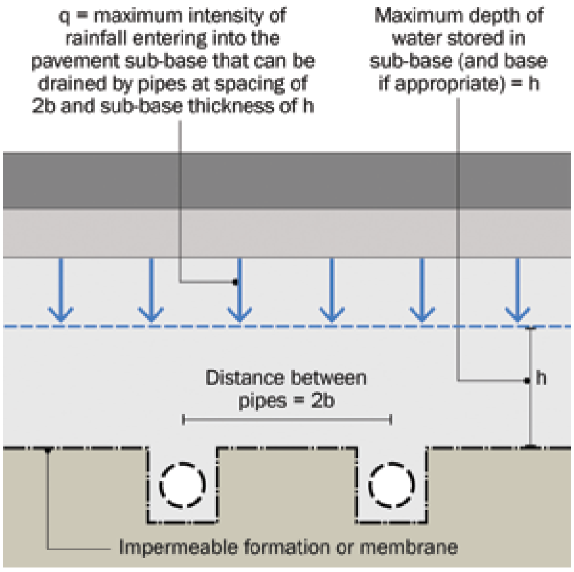


Figure 20.22 Outfall pipe spacing (after Interpave, 2010)

Water should flow horizontally through the sub-base to reach the outlet collection systems and there should be sufficient capacity in any aggregate to convey the rates of flow required. Horizontal water flows can very crudely be estimated using Darcy's law (ICPI, 2011) – **Equation 20.2.**

EQ. 20.2

Darcy's law to calculate sub-base flow

$$Q = A.k.i$$

Where

Q = flow capacity of sub-base (m^3/s)

A = cross-sectional flow area, ie height × width of sub-base through which water is flowing (m^2)

k = coefficient of permeability of sub-base (m/s) (minimum value is specified in **Section 20.11**.)

i = hydraulic gradient (m/m) (The hydraulic gradient is the head of water driving the flow. For this purpose, it is assumed to be the slope of the subgrade towards the outlet. This is not the true hydraulic head, but is a simple approximation which is generally conservative.)

Outflow from the sub-base should be via a system of perforated pipes or fin drains that provide a large surface area for water to flow into. Outlets that comprise simply the open end of a pipe (wrapped in geotextile) are prone to clogging and are not suitable. Perforated pipes should extend at least 1 m into the sub-base, and the pipes should be slotted or have circular holes formed as part of the manufacturing process. Perforations should not be made in pipes by site operatives. The perforated section of pipe should have sufficient flow capacity through the walls to manage the anticipated flows, and the perforations should be compatible with the aggregate size, such that migration of aggregate particles into the pipe is prevented. The capacity of the pipe to convey water should also be sufficient to manage anticipated flows. The open ends of any pipes that end in contact with gravel should be capped.

20.5.2 Interception design

Studies have shown that the frequency of runoff from all types of pervious pavements is significantly reduced when compared to gulley and pipe systems draining impermeable surfaces. Kellagher (2013) found that very high levels of compliance with Interception criteria are achievable through the use of pervious pavements, providing there is a nominal level of infiltration available. This is because, during small events, the water soaks into the pervious surface, laying course and sub-base, and is released back into the atmosphere through evaporation once the rainfall has stopped. In unlined systems (Type A and B pavements), infiltration can also deliver Interception. The results of various studies demonstrating the ability of pervious pavements to provide Interception storage are summarised in **Table 20.3**. These show that runoff typically does not occur from pervious pavements for rainfall events up to 5 mm.

TABLE 20.3 **Interception storage provided by pervious pavements**

Site	Reference	Type of pervious pavement	Interception storage (rainfall required to initiate runoff – mm)		
			Maximum	Minimum	Average
National Air Traffic Control Services, Edinburgh	Pratt *et al* (2001)	CBPP	17.2	2.6	7.3
Kinston, North Carolina	Collins *et al* (2008)	CBPP	> 5	n/a	n/a
Sydney, Australia	Rankin and Ball (2004)	CBPP	16	2.5	5[1]
North Carolina	Collins *et al* (2008)	Concrete grass grid	—	—	6
Toronto	Drake *et al* (2012)	CBPP and porous concrete	—	—	7

Note

1 Typical from curve fit of results

Permeable pavements can be combined with rainwater harvesting systems, which is another approach to providing Interception (**Chapter 11**).

20.5.3 Peak flow control design

Permeable pavements help reduce flow rates from a site by providing attenuation storage. The available storage volume is provided by the void space in the sub-base:

Available attenuation storage in sub-base =
Volume of sub-base × porosity in the soil/aggregate/
geocellular layer designed to be the storage volume

On sloping sites, the volume of storage will be reduced compared to the same area on a level site. The volume of storage in a sloping site is given by:

Available attenuation storage in sub-base =
0.5 × L × B × T × porosity in the soil/aggregate/geocellular layer designed to be the storage volume

Where

L = length of sub-base where water can be stored = T/tan β

T = thickness of sub-base measured vertically

B = width of sub-base where water can be stored

β = slope angle

A flow control structure is required to constrain the rate of water discharged from the sub-base via an outlet pipe. Where designs are accommodating small areas of pavement (eg for driveways and access routes), it may be appropriate to link adjacent pavements together so that the control system can be larger. The required storage volume for peak flow control should be assessed in accordance with **Section 24.9.**

20.5.4 Volume control design

Contribution of permeable pavement systems to volume control should be evaluated using standard methods, based on expected infiltration rates and/or available attenuation storage and specified flow controls. Assessment of volumetric control should follow the method described in **Chapter 3**.

To achieve suitable volumetric control, overflows to different areas of the drainage system may be required or alternatively the flow control at the outlet can be designed to provide a variable discharge. The use of rainwater harvesting (using the permeable pavement as the storage) can also be used to help to achieve a volumetric reduction in runoff.

20.5.5 Exceedance flow design

Pervious pavement systems should include exceedance event management as an integrated part of the system design. One option is to use gullies set slightly above the elevation of the pavement. This allows for some ponding above the pavement surface to be used for extra storage.

Temporary storage of runoff from extreme events above the pavement surface should not be permitted where there is a risk of surface clogging from deposited sediments and other debris.

▶ Further guidance on exceedance design is provided in **Section 24.12**.

20.6 TREATMENT DESIGN

Permeable pavement drainage has been shown to have decreased concentrations of a range of surface water pollutants when compared to impermeable surface drainage, including heavy metals, oil and grease, sediment and some nutrients (Pratt *et al*, 1995 and 1999, James and Shahin, 1998, Brattebo and Booth, 2003, Bean *et al*, 2007, Drake *et al*, 2012). All but nutrient removal has been repeatedly demonstrated in many research locations. Evidence of the removal efficiencies of permeable pavements are included in **Chapter 26, Annex 3**.

Because most permeable pavements substantially reduce the volume of runoff and outflow, it is logical that they will also significantly reduce pollutant loadings to receiving surface waters. The acceptability of allowing infiltration from the pavement will depend on the extent of the likely runoff contamination and site characteristics (see **Chapter 4, Table 4.3**).

Several studies confirm that permeable pavements demonstrate significantly lower total pollution loadings than standard pavements (Day *et al*, 1981, Rushton, 2001, Bean *et al*, 2007, Drake *et al*, 2012).

Treatment processes occurring within pervious pavements include:

- filtration of silt and the attached pollutants – the majority of silt is trapped within the top 30 mm of the jointing material between the blocks
- biodegradation of organic pollutants, such as petrol and diesel within the pavement construction
- adsorption of pollutants (pollutants attach or bind to surfaces within the construction) which depends on factors such as texture, aggregate structure and moisture content
- settlement and retention of solids.

Enhanced soils can also be used to improve treatment within the pervious pavement system. This can be achieved using either proprietary systems or by the addition of small amounts of substrate, or materials with a higher adsorption capacity than conventional aggregates (sawdust, peat, clay soils, granular activated carbon can all increase adsorption). The added materials should not reduce the structural or hydraulic performance of the aggregates. The required microbes are usually already present in the ground and further applications of microbes is not required.

The pollutants are trapped within the construction at various locations according to the type of pervious construction. It has also been found that oils held in some types of pervious construction may be degraded by microorganisms (Pratt, 1999). Hence oil saturation of the pavement is unlikely where supply is evenly spread over time. A major oil spill could overwhelm the system, but this risk can be mitigated by using specialist oil adsorbing geotextiles within the construction (a heavier weight geotextile will be more effective, especially if it has been specifically developed to attract oil). It is thought likely that nutrients occurring in the environment near pervious pavements, such as in grass cuttings, leaves and animal droppings, may well provide the required stimulus for indigenous microbial community development. For sites with a low risk of oil spillage, there is no need to use geotextile between the bedding layer and sub-base for pollution removal performance, because the geotextile makes little if any difference to removal of other pollutants.

If geocellular storage is used instead of aggregate sub-base, the benefits of treatment within the sub-base gravels will be lost. However, the use of a horizontal geotextile above the geocellular units can help mitigate this loss (Puehmeier and Newman, 2008), and has been demonstrated to provide comparable performance. Also, a significant proportion of the pollution removal has been demonstrated to occur in the top of the jointing voids in concrete block permeable paving, the top layer of porous asphalt (if the surface layer has a smaller grading) and in the grass/rootzone layer of grass systems.

If increased confidence in the removal of nitrogen has to be achieved then water would have to be fed from the sub-base material below the pervious pavements to the next stage of the Management Train, specifically designed to optimise nutrient removal. This could be achieved by linking up the pavements to a pond or series of ponds or bioretention system with an anaerobic zone as these have better removal rates for phosphorous and nitrogen. Concrete grass grid pavers filled with sand have been found to be more effective at removing total nitrogen than other types of pervious surface (Urban Waterways, 2008).

Drake *et al* (2012) found clear differences in water quality issuing from CBPP and porous concrete. The two surfaces appear to capture different pollutants. This may be the result of the higher pH conditions within the porous concrete affecting metal adsorption. There was also initial leaching of some contaminants from the concrete (phosphate and high pH). Porous concrete also takes time to stabilise and, in the longer term (1 year +), performance seems to approach that of CBPP.

The treatment design should ensure that the surface layer has sufficiently small voids to trap silt within 30 mm of the surface but still be permeable enough to allow water to flow into the sub-base. Porous asphalt, porous concrete, reinforced grass, resin bound gravel and concrete block permeable paving with 2/6.3 jointing material should all meet this requirement.

20.7 AMENITY DESIGN

Pervious pavements can provide amenity in the form of both the usefulness (ie they afford flexible and multiple use of space for a wide range of activities) and the visual aspects of the surface materials (especially grass systems). However, there are no specific design requirements to achieve amenity over and above the choice of surface as part of the overall planning, architectural or landscape design.

20.8 BIODIVERSITY DESIGN

Pervious pavements do not provide any direct biodiversity benefits, although they are very useful for treating and controlling water to maximise the biodiversity in any downstream ponds or wetlands. There are no specific design requirements or approaches for biodiversity.

20.9 STRUCTURAL DESIGN (PAVEMENT ENGINEERING)

20.9.1 Introduction to structural pavement design

The pavement design philosophy introduced by Powell *et al* (1984) is still the basis for flexible pavement design in the UK. The soil below a road pavement is usually much weaker than the road pavement materials and cannot support direct wheel loads. The main principle of road pavement design is that the constructed layers distribute the concentrated loads from wheels to a level that the soil below the road (referred to as the subgrade) can support without failure or excessive deformation. At the surface of the road, the pressure from wheels is the highest, and so strong, high quality materials are used in the upper layers (eg concrete, asphalt, block paving). The pressure reduces with depth allowing weaker materials to be used lower in the pavement (as sub-base and capping layers). In the longer term, the capping and/or sub-base prevent groundwater reaching the bound upper layers.

The main layers that are placed to form a road pavement are shown in **Figure 20.23**.

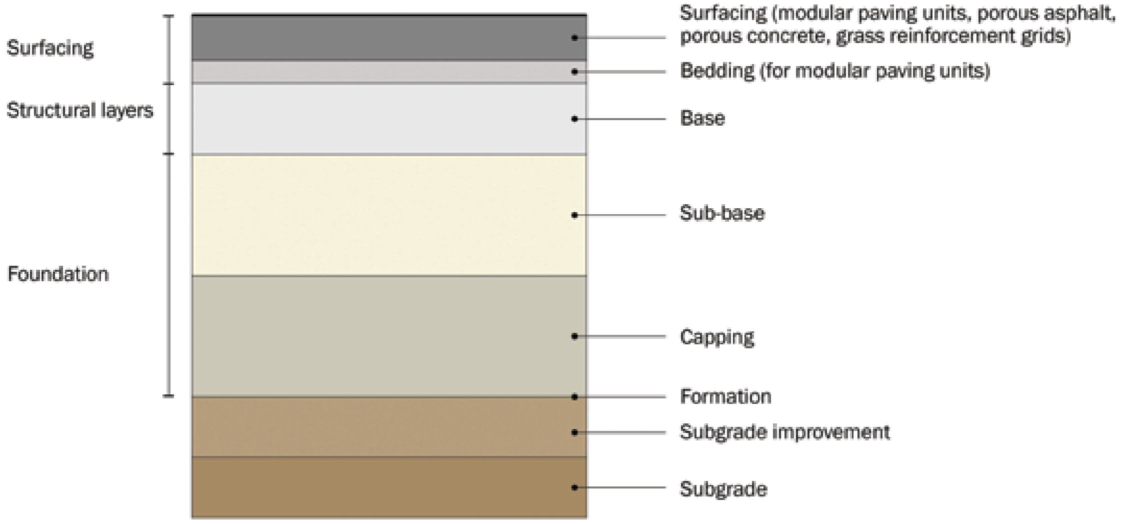


Figure 20.23 Layers in a road pavement construction

The capping and sub-base layer are known as the foundation and should give sufficient load-spreading to provide an adequate construction platform and base for the overlying pavement layers. The asphalt, asphalt concrete, concrete, blocks or other pavement materials are referred to as structural or surface layers and should not crack or suffer excessive rutting under the influence of traffic. One of the main structural layers is the base, which will usually comprise either porous asphalt, asphalt concrete or hydraulically bound material. The base layer is of particular importance in concrete block paving designed to carry regular HGV traffic.

20.9.2 Pervious pavement structural design principles

Although no approved structural design methods for pervious pavements exist in the UK, there are a number of general principles that should be followed when pervious pavements are designed. Guidance by Pratt *et al* (2001) should be referenced for supporting detail on pervious pavement design methods and materials.

Normal road pavement materials are not intended to allow water into the construction. Pervious pavements do allow water into the construction, and this means that the pavement should be designed and the materials specified, so that it can support traffic when saturated while allowing water to flow freely through it. The materials used for pervious pavement construction should be graded to give the right balance between achieving good structural performance and providing sufficient permeability and void space for water storage. Care should be taken to ensure that loss of finer particles between unbound layers does not occur, as this can reduce the strength of granular layers. Geotextile can be laid between unbound layers to prevent this from occurring. Where a geotextile is not provided between laying course and sub-base, the aggregates should meet standard geotechnical filter criteria (**Section 30.5.3**).

The other overriding consideration is that the surfacing will be sufficiently durable and can withstand the likely turning and impact forces from traffic with damage (eg spreading of blocks under excessive traffic shear forces).

In general, the approach taken to all surfaces is as follows, following Knapton *et al* (2012):

1 For lightly trafficked pavements, the loads applied by wheels are the critical factor, and the guidance for those pavements is based upon wheel loads.

2 For more heavily trafficked highway pavements, the pavements are designed on the basis of the cumulative number of standard 8000 kg axles.

20.9.3 Determination of the CBR value for design of pervious pavements

Design CBR value

Californian bearing ratio (CBR) varies inversely with moisture content (as the latter increases the CBR value decreases). The equilibrium CBR value is the long-term value that occurs once the pavement is constructed and the moisture content of the subgrade soil comes into equilibrium with the suction forces within subgrade pore air spaces. Suction forces can occur as a result of unloading due to excavation. Changes in groundwater levels or wetting as a result of water storage in the sub-base will also affect the equilibrium CBR value. Equilibrium CBR values should be used for permeable pavement design. This can be determined by carrying out laboratory CBR tests in accordance with BS 1377-4:1990 at the equilibrium moisture content as described by Powell *et al* (1984). For Type A and B pavements the CBR should be tested after saturation. The ICPI (2011) recommends a 96-hour saturation period.

Alternatively, the value should be estimated based on the type of soil (plasticity index and grading) following the guidance by Powell *et al* (1984) and BS 7533-13:2009, as provided in **Table 20.4**.

TABLE 20.4 **Equilibrium subgrade CBR estimation**

Soil type	Plasticity index	Guideline equilibrium CBR Value for pervious surface design[1, 3] (%)
Heavy clay	70	2
	60	2
	50	2
	40	2.5
Silty clay	30	3
Sandy clay	20	4
	10	3
Silt[2]	–	1
Sand (poorly graded)	–	7
Sand (well graded)	–	10
Sandy gravel (well graded)	–	15

Note

1 Assumes thin construction. If pavement thickness (from surface to subgrade) is greater than 1200 mm (see HA, 2009).

2 Estimated assuming some probability of material saturating.

3 These CBR values assume a high water table and that the subgrade may be wetted during the life of the pavement.

The highest values of plasticity index measured on a site should be used (to give the lowest CBR value) for the design, unless there are a substantial number of results available to allow the mean or other statistical value to be used with confidence, but if the mean is used, there will be an increased risk of pavement failure in some areas. It may be possible to remove soft spots and therefore ignore those low CBR values which relate to the removed material.

On sites where the CBR varies from place to place, appropriate designs may be provided for different parts of the site using the lowest CBR recorded in each part.

Once the subgrade is exposed during construction, the CBR value of the soil should be confirmed by laboratory testing of CBR samples (BS 1377-4:1990) or using *in situ* methods (BS 1377-9:1990). This is the short-term CBR value at the time of construction. If it is found to be less than the design CBR, the subgrade should either be improved to achieve the design CBR, or the foundation thickness should be redesigned. The reason for this is because construction during very wet weather can adversely affect the soil strength and lead to lower equilibrium CBR values.

In summary the final design CBR value should be the lower of:

1. the equilibrium CBR value obtained from CBR tests at equilibrium moisture content (saturated for 96 hours for Type A and B) or based on plasticity and grading results using the correlations above
2. the short term CBR value obtained from CBR tests on the subgrade, taken once it is exposed for construction.

Subgrade with low CBR (CBR < 2.5%)

British Standard BS 7533-101:2015 specifies that the minimum permitted design CBR is 2.5% for normal pavements and this also applies to pervious pavements. Subgrades with a lower design CBR are considered unsuitable to support a pavement foundation. In these cases, a subgrade improvement layer should be provided to permanently improve the load-bearing capacity of the subgrade. This can be achieved by removing the weak material to sufficient depth and replacing it with suitable fill material. The thickness removed may typically be 0.5–1.0 m. Although the new material may be of better quality, the new design CBR should be assumed to be equivalent to 2.5%, in order to allow for effects of any softer underlying material and the potential reduction in the strength of the replacement material to its long-term CBR value.

The existing subgrade materials may also be improved by the addition of lime and/or cement to give an acceptable long-term CBR value if the areas with a low CBR are extensive. This will only be possible with Type C pavements (no infiltration). The impact of water on the stabilised materials should be carefully considered.

The incorporation of a geosynthetic material into the foundation design may also overcome the issue of a weak subgrade. Specialist advice should be sought to adopt an alternative design CBR value that may be necessary, based on testing or previous experience with the specific geosynthetic and the materials being used on the scheme.

20.9.4 Traffic categories

Pervious pavements can be designed to carry any volume of traffic loads. **Table 20.5** defines traffic loads in terms of traffic categories. These traffic categories can be used for the design of any type of surfacing including porous asphalt and other materials and are used as the basis for the structural design of all types of surface discussed in this manual.

TABLE 20.5 Traffic loading categories for pervious pavement design

Traffic category (BS 7533)	Standard axles per day	Lifetime traffic (msa)	NRSWA road type	Maximum anticipated axle load (kg)	Example number of commercial vehicles per day[1]	Typical application
11	Areas with axle loads greater than permitted by the Road Vehicles (Construction and Use) Regulations 1986 as amended are not included in this document					
10	≤ 4,000	≤ 60	0	Site specific (see Knapton, 2007)		Adopted highways and commercial/industrial developments used by a high number of commercial vehicles Ports and airport landside Bus stops and bus lanes
9	≤ 2,000	≤ 30	1	Site specific (see Knapton, 2007)		
8	≤ 700	< 10	2	8000	Approx 420	
7	≤ 275	< 2.5	3	8000	Approx 170	
6	≤ 60	< 0.5	4	8000	Approx 35	Adopted highways and other roads used by a moderate number of commercial vehicles Pedestrian areas subjected to regular overrun of commercial vehicles Industrial premises Petrol station forecourts
5	≤ 5	< 0.05	n/a	8000	Approx 3	Pedestrian areas subjected to occasional overrun of commercial vehicles and maintenance/cleaning machines Car parks receiving occasional commercial vehicular traffic Railway platforms excluding edge
4	1	n/a	n/a	8000	Mainly car or pedestrian traffic with emergency HGV vehicles only	Urban footways with no planned vehicular overrun Pedestrian areas or car parks used by light commercial vehicles emergency vehicles and by maintenance vehicles
3	0	n/a	n/a	2,000	No HGV	Small car parks subject to car, light van and motorcycle access
2	0	n/a	n/a	1,000	No HGV	Pedestrian and cycle areas, domestic driveways
1	0	n/a	n/a	1,000	No HGV	Pedestrian-only areas, including domestic applications
0	0	n/a	n/a	0	No vehicular traffic	No requirement (decoration)

Note

1 Based on 1.7 standard axles per vehicle.

No commercial vehicle traffic loading

Site categories 0, 1, 2 and 3 should only be selected where it can be ensured that no commercial vehicles use the pavement, for example where bollards or height barriers have been installed.

In determining the site category, the use of the surface of the pavement by any construction traffic should be assessed and allowed for.

Pedestrian loading and maintenance vehicles

Open areas are now being increasingly maintained by mechanical sweepers and other collection vehicles that can have surprisingly high wheel loadings and other detrimental effects (eg suction sweepers) on paved areas. Their use should be assessed in determining the traffic category appropriate to adopt for the design.

Amenity areas

In areas where there is no possibility of vehicular access (eg patios and private garden paths), a category 0 or 1 design may be adopted

Site traffic

Where the site is to be used for construction traffic, the layer to be used by that traffic should be of adequate strength for the use. Normally the completed base should be adequate, but in case of doubt (eg for a large-scale development), an estimate of the traffic should be made and a pavement design carried out using current design guidance for bound or unbound pavements.

In areas not subject to commercial vehicle traffic, the design should consider loading during construction and maintenance of adjacent areas, and other vehicles that might access the area, including emergency vehicles. Their use should be allowed for in the design.

Design life

A 20-year design life should be generally applicable (structural) unless access for possible maintenance of the base is likely to be difficult or expensive, in which case a longer design life may be advisable. Where the pavement serves a finite area, zero growth in traffic is likely to be applicable. If calculated growth figures are available, these should be used to ascertain the number of standard axles.

20.9.5 Structural design approaches

The philosophy for conventional (ie non-pervious) pavement design is that the sub-base and/or capping layer is only influenced by the strength of the subgrade, with the thickness of the upper structural layers (base and surface courses) influenced by traffic loadings. The design method used in BS 7533-13:2009 for concrete block permeable paving is different, in that the traffic load does have an influence on the thickness of the sub-base and/or capping layer. Knapton *et al* (2012) have combined the two approaches for pervious pavements and used maximum wheel load design for lightly trafficked areas of pervious paving and a conventional axle fatigue approach for more heavily trafficked pavements. They also extended the scope for pervious pavements to heavy duty industrial pavements by applying the design approach proposed by Interpave (Knapton, 2007).

In the UK, the established design methodologies for flexible pavements with either an asphalt or hydraulic bound base can also be used to design porous asphalt pavements for heavily trafficked roads (Chaddock and Nunn, 2010). Structural design of pavements is most important for those surfaces used in areas subject to heavier or more frequent HGV traffic.

Analytical design is becoming more widely accepted in pavement engineering and can be applied to pervious pavements. Analytical design is a very useful approach, which allows the use of different porous or permeable materials, and it should be encouraged. However, it is vital that the material properties assumed in the design are achieved during construction (eg the stiffness of concrete block permeable paving should reflect normal construction practice and not rely on very high quality workmanship) and an appropriate site testing regime will be required. Also, the materials used in construction should provide all the other necessary attributes (eg durability and providing suitable skid resistance). Most analysis uses a simplified multi-layer linear elastic model, although finite element analysis can also be used (Knapton *et al*, 2012). An element of judgement will still be required in the design, based on experience of the performance of different materials. This approach can be used for a wide range of traffic conditions. In the USA, the ICPI (2011) has published a design program for concrete block permeable paving called Permeable Design Pro. Although this is based on USA design methods, there is no reason why it cannot be applied to UK design of concrete block permeable paving. One of the key design parameters in analytical approaches is the stiffness of the various materials, and values are provided in **Table 20.6**.

TABLE 20.6 **Stiffness of various materials used in pervious surface construction**

Material	Stiffness	Source
Porous asphalt	2 GPa	Chaddock and Nunn (2010)
	3.2–7.1 GPa	Chopra *et al* (2011)
Porous concrete	Range 25–45 GPa Typical 38 GPa	Dynamic modulus, Chaddock and Nunn (2010)
Permeable sub-base for use below all types of surfacing	93–138 MPa 250–400 MPa (but these would need reducing to allow for saturation by 40–70%, which in worst case would give 100–160 MPa)	ICPI (2011) Shackel (2006)
Concrete block permeable pavers	1000–4500 MPa depending on type of block	Shackel *et al* (2000)

Resilient modulus is a measure of stiffness under loads that are applied quickly (such as traffic loads). Shackel *et al* (2000) found that there was little difference in resilient modulus between permeable and non-permeable versions of block paving and also between different laying patterns. Paver shape was found to have a significant impact of resilient modulus.

Note that when measuring the stiffness of permeable sub-base materials on site, they are likely to return lower values than when unconfined on the surface. Experience, analysis (Interpave, 2007) and also testing (Chaddock and Nunn, 2010) have shown that once confined by the overlying pavement construction the stiffness will increase.

20.9.6 Structural design considerations for different surface types

The following sections provide specific information on structural design for various surfacing materials.

Grass reinforcement and resin bound materials

This section covers reinforcement grid systems that are plastic or concrete and infilled with grass or gravel. It also covers resin bound materials. There is no recognised UK design standard for these types of pervious pavements. Often designers rely on recommendations made by manufacturers. However, the surfacing provides very little contribution to the load-bearing capacity of the pavement structure and therefore the sub-base thicknesses used for asphalt or CBPP can be applied to these types of surface (ICPI, 2011).

The systems are often used with normal Type 1 sub-base below (ie not for water storage), in which case standard pavement design approaches should be used. If coarse-graded aggregate is used below the surfaces to store water, the sub-base depths in **Table 20.7** can be used. A capping layer or increased thickness of coarse-graded aggregate may be required where the CBR values are less than 5%. Where used with coarse-graded aggregate sub-base, a geotextile will be required between the sand bedding/growing layer and the sub-base, otherwise the sand will be washed down into the sub-base. These surface types are not recommended for load classes above site category 4.

TABLE 20.7 **Typical construction thickness for grass reinforcement and resin bound materials over subgrade of 5% CBR or greater**

Traffic category (BS 7533)	Grid	Bedding layer	Sub-base CGA
4	Varies	50 mm	300 mm
3	Varies	50 mm	225 mm
2	Varies	50 mm	150 mm
1	Varies	50 mm	100 mm
0	Varies	50 mm	Sufficient to provide suitable construction base

The sections in **Table 20.7** apply in the case of subgrades of 5% CBR or greater. For pavements over lower CBR values that are trafficked by vehicles, the following should be provided:

- 1% CBR subgrade improvement required (**Section 20.9.3**)
- 2% CBR subgrade improvement layer required (may be incorporated into capping layer to provide a total layer thickness of 350 mm)
- 2.5% CBR 300 mm capping
- 3% CBR 225 mm capping
- 4% CBR 150 mm capping

The capping layer design can also incorporate geogrid(s), which may reduce the required thickness of material. However, the sub-base and capping layer thickness may need increasing to allow for use by construction vehicles.

When used over open-graded sub-base such as Type 3, a geotextile separation layer will be required to prevent the sand infill/bedding layer from being washed into the underlying sub-base. Trials by Chaddock and Jones (2007) have shown that great care is needed in lapping the geotextile to ensure that washout does not occur. It is recommended that an overlap of at least 500 mm is provided, and that care is taken at the edges to ensure that localised washout cannot occur (lap the geotextile upwards at the edges and suitable folds at corners to contain the bedding sand).

Porous asphalt

Porous asphalt can be designed using analytical pavement design procedures using appropriate values of resilient modulus for the materials specified in the pavement. Alternatively, the advice in Chaddock and Nunn (2010) may be used to design the porous asphalt layers. Another approach is to combine the sub-base and other layer thicknesses specified by Knapton *et al* (2012) but replace the concrete blocks and bedding layers with a porous asphalt layer. This latter approach is the basis for **Table 20.8**. Further advice on the use of porous asphalt in car parks and private drives is provided by MPA (2009). Detailed guidance on suitable mixtures should always be obtained from the supplier.

The sections in **Table 20.8** apply in the case of subgrades of 5% CBR or greater. For pavements over lower CBR values that are trafficked by vehicles, the following should be provided:

- 1% CBR subgrade improvement required (**Section 20.9.3**)
- 2% CBR subgrade improvement layer required (may be incorporated into capping layer to provide a total layer thickness of 350 mm)
- 2.5% CBR 300 mm capping
- 3% CBR 225 mm capping
- 4% CBR 150 mm capping

TABLE 20.8 Typical construction thickness for porous asphalt over subgrade with 5% CBR or greater

Traffic category (BS 7533)	Porous asphalt	Base HBCGA[1]	Sub-base CGA[2]
11	Areas with axle loads greater than permitted by the Road Vehicles (Construction and Use) Regulations 1986 as amended are not included in this document[3]		
10	Asphalt requires specialist consideration and specification	Site specific using Interpave guide for heavy duty pavements (Knapton, 2007)	150 mm
9	Asphalt requires specialist consideration and specification	Site specific using Interpave guide for heavy duty pavements (Knapton, 2007)	150 mm
8	Design following Chaddock and Nunn (2010)[4]	300 mm HBCGA	150 mm
7	Design following Chaddock and Nunn (2010)	200 mm HBCGA	150 mm
6	180 mm 80 mm	– 125 mm HBCGA	150 mm 150 mm
5	160 mm 80 mm	– 100 mm HBCGA	150 mm 150 mm
4	150 mm	–	300 mm
3	120 mm	–	225 mm
2	70 mm (assumes hand lay)	–	150 mm
1	70 mm (assumes hand lay)	–	100 mm
0	70 mm (assumes hand lay)		Sufficient to provide suitable construction base

Note

1. HBCGA refers to hydraulically bound coarse-graded aggregate (conforming to BS EN 14227-1:2013), minimum cement content 3%, strength class C5/6 as defined in BS EN 14227-1 and minimum permeability 10,000 mm/hr when tested in accordance with ASTM C1701M-09 or other suitable test).
2. The sub-base CGA depths are minimum values that correspond with the equivalent thicknesses provided in **Table 20.10** for modular surfacing. The sub-base CGA and any capping layer can also be designed to Foundation Class 2 in accordance with HA (2009).
3. Special vehicles (SV) fall outside the Road Vehicles (Construction and Use) Regulations 1986. SV vehicles comply with the Road Vehicles (Authorisation of Special Types) (General) Order 2003 or the Individual Vehicle Special Orders. They have higher axle loads and weights and are commonly known as abnormal loads.
4. The Chaddock and Nunn (2010) report was based on a pilot study. The tables in the report showing pavement designs for up to 80 msa (million standard axels) are an extrapolation of test data and have not been validated in full size schemes. If designs are required for traffic category 7 and above, specialist advice should be obtained from suppliers about whether porous asphalt is suitable and to provide an appropriate specification.

The capping layer design can also incorporate geogrid(s), which may reduce the required thickness of material. However, the sub-base and capping layer thickness may need increasing to allow for use by construction vehicles.

Note that porous asphalt may not be suitable as a surfacing in some locations (eg petrol forecourts, ports or bus stops) due to either the risk of degradation resulting from fuel spills or the nature of the risk of surface deformation resulting from the possible range of traffic forces.

Porous concrete

Porous concrete is not widely used at present in the UK. However, it is used in the USA, where comprehensive design and construction guidance is available (eg ACPA, 2011, CRMCA, 2009, ACI, 2010). A structural design programme for pervious concrete pavement design is available from the ACPA (called PerviousPave) and this can be adapted to design porous concrete paving for UK conditions. The equations used in the programme and the background information is provided by the ACPA (2011). Obla (2007) indicates that numerous applications have used a 125–150 mm thick pervious concrete layer over 150 mm sub-base. Field performance of these projects has shown that they are adequate to handle the traffic loads expected in car parks with mainly passenger cars with very occasional HGVs (trash trucks). Where heavier loads and higher traffic are expected, then US experience suggests using a thicker layer of porous concrete (200–300 mm).

Porous concrete is a near-zero-slump, open-graded material consisting of portland cement, coarse aggregate, admixtures and water. It has little or no fine aggregate (ACI, 2010). The combination of these ingredients will produce a hardened material with connected pores, 2–8 mm in size, which should allow water to pass through easily. The porosity can be 15–35%, with typical compressive strengths of (2.8–28 MPa). Porous concrete is laid as a plain concrete slab without reinforcement.

Recommended concrete and sub-base CGA thicknesses are provided in **Table 20.9**.

TABLE 20.9 **Typical construction thickness for porous concrete over subgrade with 5% CBR or greater**

Traffic category (BS 7533)	Porous concrete (plain slab)	Sub-base CGA
11	Areas with axle loads greater than permitted by the Road Vehicles (Construction and Use) Regulations 1986 as amended are not included in this document	
10	Site specific design	
9	Site specific design	
8	Site specific design	
7	Site specific design	
6	Site specific design	
5	150 mm	300 mm
4	135 mm	300 mm
3	125 mm	225 mm
2	125 mm	150 mm
1	100 mm	100 mm
0	100 mm	Sufficient to provide suitable construction base

The sections in **Table 20.9** apply in the case of subgrades of 5% CBR or greater. For pavements over lower CBR values that are trafficked by vehicles, the following should be provided:

- 1% CBR subgrade improvement required (**Section 20.9.3**)
- 2% CBR subgrade improvement layer required (may be incorporated into capping layer to provide a total layer thickness of 350 mm)
- 2.5% CBR 300 mm capping
- 3% CBR 225 mm capping
- 4% CBR 150 mm capping

The capping layer design can also incorporate geogrid(s), which may reduce the required thickness of material. However, the sub-base and capping layer thickness may need increasing to allow for use by construction vehicles.

The designs in **Table 20.10** have been assessed using ACPA (2011) assuming a 40-year design life, 0% growth, resilient modulus of sub-base CGA is 110 MPa and 28-day flexural strength of porous concrete is 2.8 MPa. For CBR less than 5% use the factors above to increase capping layer thickness or design using ACPA (2011).

Because there is currently no track record of using porous concrete in the UK, it is recommended that expert advice is obtained to undertake site specific designs for site categories 6–10.

Modular surfacing (including concrete block permeable paving)

This can be used for a wide range of traffic conditions from light to very heavy duty pavements. BS 7533-13:2009 provides standard thicknesses for the pavement layers, although these can be adjusted if materials with a different stiffness are used following the approach described by Knapton *et al* (2012) or using the ICPI (2011) design approach.

The structural design of CBPP suggested in **Table 20.10** has been developed from the approach of Knapton *et al* (2012). Their approach is based on a combination of finite element analysis of static wheel loads and analysis of full-scale test results. The main difference between **Table 20.12** and the Knapton *et al* (2012) approach is that the table provides the same construction thickness for all of Types A, B and C pavements. This is because any effect of infiltrating water should have been taken account of when choosing the design CBR value. In general, Types A and B pavements will result in lower design CBR values because of the presence of water in contact with the subgrade. The waterproofing layer and sand protection layer (or geotextile protection) provided in Type C systems do not have any influence on the structural design and therefore are not included in the table for structural design.

The design layer thickness has been checked using the guidance provided by the ICPI (2011). This approach makes assumptions about the default properties of the materials used in each layer, which are summarised in **Table 20.11**.

TABLE 20.10 Typical construction thickness for modular paving over subgrade with 5% CBR or greater

Traffic category	Type of surface – minimum thickness				Bedding layer nominal thickness	Base HBCGA[1] (porous) or AC (cored)	Sub-base CGA[2]	Design basis
	Concrete/clay blocks	Natural stone slab	Concrete flag	Setts				
11	Areas with axle loads greater than permitted by the Road Vehicles (Construction and Use) Regulations 1986 as amended are not included in this document[3]							
10					Site specific using Interpave guide for heavy duty pavements (Knapton, 2007)			Knapton (2007)
9					Site specific using Interpave guide for heavy duty pavements (Knapton, 2007)			Knapton (2007)
8	80 mm	Seek advice from supplier			50 mm	300 mm HBCGA or 220 mm AC32	150 mm	ICPI (2011)
7	80 mm				50 mm	200 mm HBCGA or 130 mm AC32	150 mm	
6	80 mm				50 mm	125 mm HBCGA or 90 mm AC32	150 mm	
5	80 mm				50 mm	100 mm HBCGA or 70 mm AC32	150 mm	
4	80 mm				50 mm	–	300 mm	Knapton *et al* (2012) and ICPI (2011)
3	60 mm				50 mm	–	225 mm	
2	60 mm				50 mm	–	150 mm	
1	60 mm				50 mm	–	100 mm	
0	60 mm				50 mm		Sufficient to provide suitable construction base	

Note

1 HBCGA refers to hydraulically bound coarse-graded aggregate (conforming to BS EN 14227-1:2013), minimum cement content 3%, strength class C5/6 as defined in BS EN 14227 and minimum permeability 10,000 mm/hr when tested in accordance with ASTM C1701M-09 or other suitable test).

2 The sub-base CGA depths are minimum values that correspond with the thickness given by Knapton *et al* (2012) or from calculations using ICPI (2011). The sub-base CGA and any capping layer can also be designed to Foundation Class 2 in accordance with HA (2009).

3 Special vehicles (SV) fall outside the Road Vehicles (Construction and Use) Regulations 1986. SV vehicles comply with the Road Vehicles (Authorisation of Special Types) (General) Order 2003 or the Individual Vehicle Special Orders. They have higher axle loads and weights and are commonly known as abnormal loads.

The sections in **Table 20.10** apply in the case of subgrades of 5% CBR or greater. For pavements over lower CBR values that are trafficked by vehicles, the following should be provided (from Knapton *et al*, 2012):

- 1% CBR subgrade improvement required (**Section 20.9.3**)
- 2% CBR subgrade improvement layer required (may be incorporated into capping layer to provide a total layer thickness of 350 mm)
- 2.5% CBR 300 mm capping

- 3% CBR 225 mm capping
- 4% CBR 150 mm capping

The capping layer design can also incorporate geogrid(s) which may reduce the required thickness of material. However, the sub-base and capping layer thickness may need increasing to allow for use by construction vehicles.

AC refers to asphalt concrete (AC 32 dense 40/60 designed in accordance with BS EN 13108-1:2006.

For load class 5 and above, concrete block permeable paving should only be laid in a herringbone pattern.

Note for infiltration Type A systems the capping layer material should be sufficiently permeable to allow water to percolate through it, without it losing strength. It should also have an infiltration rate that is greater than the material below it. It should also be sufficiently durable and wear-resistant. Alternatively, an increased thickness of coarse-graded aggregate can be used. The grading for 6F2 capping (DfT, 1998) can be modified to reduce the amount of fines and make it more permeable (ie less than 5% passing the 63 microns sieve and 0–25% by mass passing the 600 microns sieve). This has been used successfully below infiltrating pavements.

TABLE 20.11 **Properties assumed in generic concrete block permeable paving design in Table 20.10**

Material	Elastic modulus (MPa)	Structural layer coefficient for use in ICPI (2011)	Poisson's ratio
Permeable pavers on a 50 mm bedding layer that meets requirements of BS 7533-13:2009	1000 (based on Shackel *et al*, 2000). Note that evidence from Knapton (2008) is that the modulus of the surface layer has very little effect on the predicted stress on the subgrade and performance of the pavement. Increasing elastic modulus values of the surface layer to justify a reduction in pavement depth is not normally recommended, as it requires extremely high construction quality, and there is no guarantee that all the joints will be completely full of jointing material for the life of the pavement to maintain an elevated elastic modulus.	0.3	0.40
AC32	6000	0.3–0.44	0.30
HBCGA (hydraulically-bound CGA) meets requirements of cement bound material category 3 (CBGM3) clause 800 series (DfT, 1998)	4000	0.24	0.25
Sub-base – coarse graded aggregate in accordance with BS 7533-13:2009	1000 Note that the main factor that affects stiffness is not the Los Angeles test (LA test) value but the grading and angular nature of the particles	0.09	0.35
5% CBR subgrade	50	n/a	0.45

Porous sports surfaces

Porous sports surfaces are usually not heavily trafficked by vehicles. An important issue for surfacing and sub-base layers used under sports pitches and games areas is that they meet the requirements of the relevant sporting federations for ball bounce etc. Most suppliers of artificial or turf surfacing will have this data or will test completed installations to demonstrate compliance. They also need to meet strict tolerances on surface levels. Usually the sub-base construction required to achieve these other requirements will be sufficient to support the likely vehicle loads (eg from maintenance vehicles).

20.10 PHYSICAL SPECIFICATIONS

20.10.1 Pre-treatment and inlets

Rainfall normally finds its way through the pervious surface via direct infiltration. However, where the pavement has sufficient hydraulic capacity, additional runoff from adjacent impermeable areas can be directed onto the pervious surface. The flow of water from the surface of adjacent paved areas should be distributed along the edge of the permeable area; it should not be channelled to a discrete point as this will cause clogging of the surface.

Runoff from adjacent roof areas can be drained directly into the sub-base, where it is likely to have very low levels of silt. However, such flows should be discharged via a silt/debris trap to prevent any risks of clogging of the pavement construction below the surface. The flow should be distributed into the sub-base using a diffuser such as the one in **Figure 20.24**.

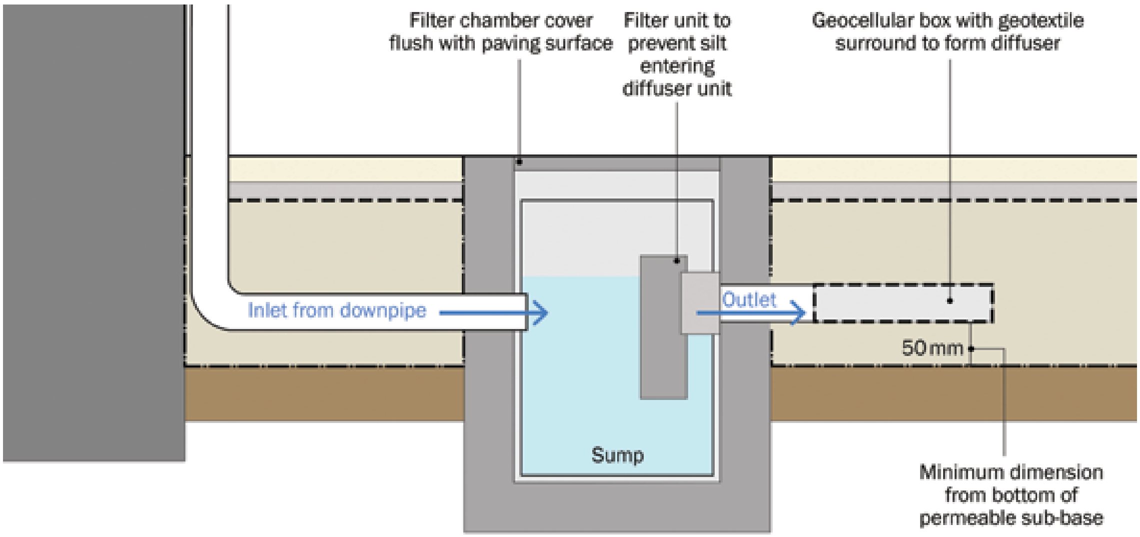


Figure 20.24 Flow diffuser to distribute roof runoff into permeable sub-base (from Interpave, 2013)

Where syphonic drainage is discharged into the sub-base, the siphon break should be before entry into the permeable sub-base via a ventilated manhole. The siphon break should be designed to provide sufficient capacity and to reduce flow velocities within the sub-base to prevent surcharging of the system. The siphon break and subsequent diffusers to distribute the flow into the sub-base should be designed in conjunction with the syphonic drainage designer.

20.10.2 Outlets

If the pavement is a Type A system that is designed to allow all water to infiltrate into the ground, there is no need for any specific outlet. If the system is a Type B or Type C, where water leaves the sub-base to flow to the next part of the drainage system, an outlet is required from the sub-base. This is usually achieved using either a series of perforated pipes (which can be within the sub-base or in trenches below (**Figure 20.25**), depending on the thickness of the sub-base and traffic loads and the strength of the pipes), or with a length of fin drain along one edge of the sub-base connected to the outlet pipe (**Figure 20.26**).

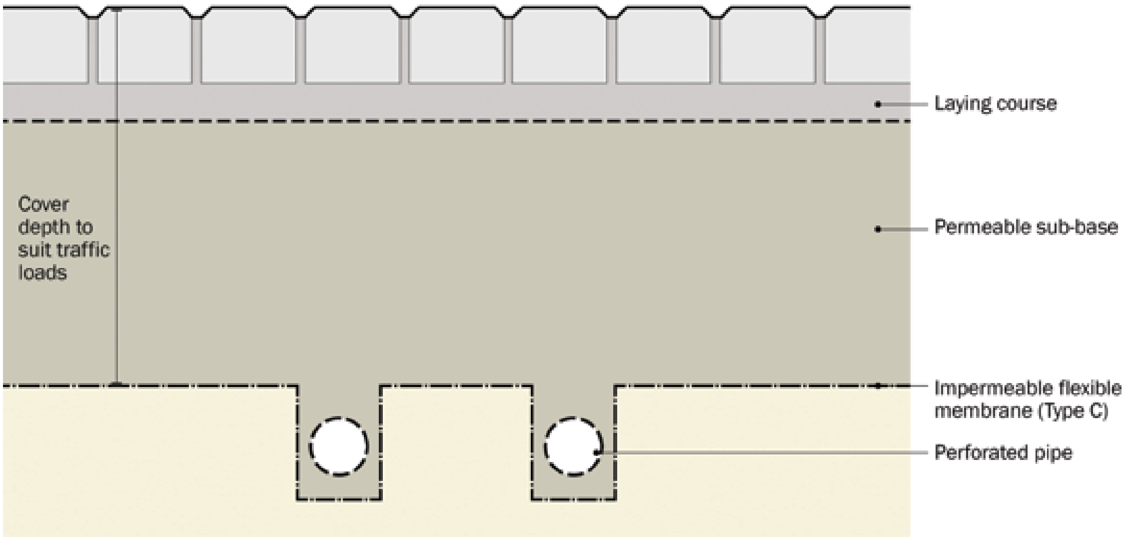


Figure 20.25 Perforated pipe outlets below sub-base

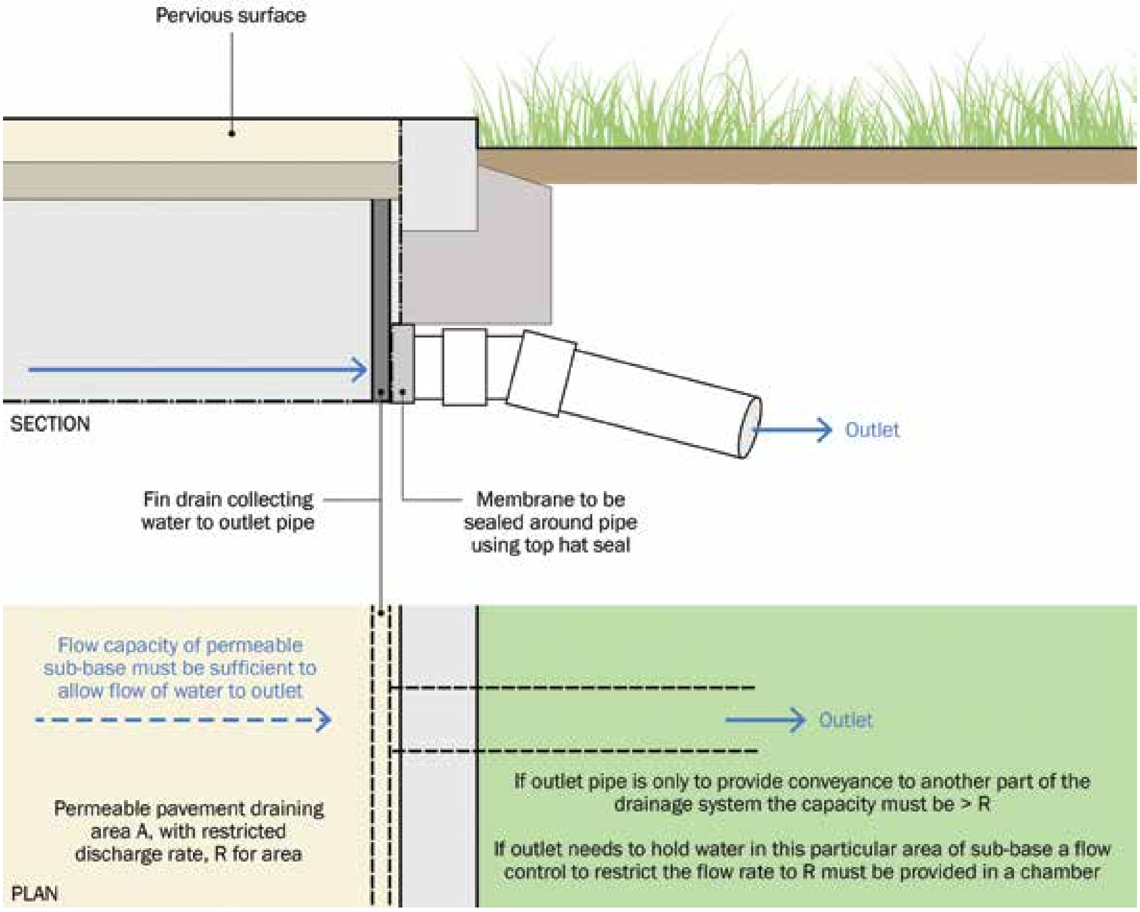


Figure 20.26 Fin drain outlet from pervious surface sub-base (from Interpave, 2010)

A well-protected observation well consisting of a 150 mm perforated pipe, or equivalent, should be placed at the downstream end of the facility. The well can be used to measure the actual emptying times of the pavement system and to keep a record performance changes with time.

20.11 MATERIALS

The sub-base beneath pervious surfacing systems has a large proportion of interconnected voids through which water can move freely and can also be stored. This material is different from a standard pavement sub-base and has to be specified so that it has sufficient permeability, porosity, strength and resistance to abrasion.

This section provides specifications for some of the key elements of pervious surfaces such as bedding and jointing material and sub-base. It does not provide a comprehensive specification for all elements that are required to meet recognised standards (eg the concrete blocks in concrete block permeable paving should meet all the same performance standards as normal concrete blocks).

20.11.1 Bedding layer and jointing material for concrete block permeable paving

Bedding and jointing material needs to be free-draining and have sufficient durability to resist wear from small movements between blocks. A typical grading specification is given in **Table 20.12**, but advice should always be sought from the pervious pavement manufacturer with regard to the exact material type that is suitable for each system. The jointing material in some systems may have smaller, 3 mm particles if the joints between blocks are smaller.

TABLE 20.12 **Bedding and jointing layer specification (2/6.3 to BS 7533-13:2009)**

BS sieve size (mm)	Percentage passing
14	100
10	90–100
6.3	80–99
2.0	0–20
1.0	0–5

The material should also meet the durability requirements in BS 7533-13:2009 (**Section 20.11.4**).

20.11.2 Sand infill and bedding layer for grass reinforcement

Sand infill to reinforced grass systems needs to be free-draining but with sufficient organic content to support plants. A root zone material (**Chapter 30**) is suitable, and there are also many other mixes recommended by suppliers of the grids. Normal topsoil is not suitable.

20.11.3 Geotextile filter characteristics

Geotextiles that act as filters should allow free flow of water, that is with zero breakthrough head. They should be manufactured from polyethylene, polypropylene or other suitable monofilament that can withstand the loads applied during construction and should have a design life equivalent to the pavement design life. They should not be adversely affected by pollutants, alkaline or acidic groundwater.

Geotextiles placed high in the pavement construction (eg between the bedding layer and sub-base of CBPP) are subject to higher stresses than those deeper in the construction (eg at the bottom of the sub-base). This needs to be evaluated and considered in the design.

▶ Further guidance on geotextiles is given in **Chapter 30**.

20.11.4 Sub-base aggregate characteristics

The sub-base should have a minimum porosity that is consistent with the design calculations (normally at least 30%). The sub-base should also have a minimum permeability of 6 × 10^{-2} m/s when tested in accordance with HA (1990).

The requirement for low fines content means that the surface loading will essentially be carried by point-to-point contact between aggregate particles in the sub-base. In order to maximise the friction between particles and thus increase strength, the particles should be rough and angular to give good interlock. Crushed rock (granite, basalt, gabbro) or concrete with > 90% fracture faces, or blast furnace slag is required to achieve this. Sand and gravel with rounded particles should not be used in pervious pavement sub-base construction. Aggregates should comply with BS EN 13242:2002+A1:2007 or BS EN 12620:2002+A1:2008. The choice is a compromise between stiffness, permeability and storage capacity. Typical gradings for sub-base aggregates are provided in **Table 20.13**. The material types are from BS 7533-13:2009 and from DfT (1998) Clause 805 Type 3 base material. However, there is no reason why other gradings cannot be used if they are more readily available and meet all the necessary requirements, and provided the base material is sufficiently durable.

TABLE 20.13 **Typical grading requirements for sub-base aggregates (after BS 7533-13:2009 and DfT, 1998)**

Sieve size (mm)	Percent passing		
	Coarse aggregate 4–40 mm (4/40) (BS 7533-13:2009)	Coarse aggregate 4–20 mm (4/20) (BS 7533-13:2009)	Type 3 sub-base 0–40 mm (0/40) (DfT, 1998)
80	100	–	100
63	98–100	–	80 -99
40	90–99	100	50–78
31.5	–	98–100	31–60
20	25–70	90–99	18–46
10	–	25–70	10–35
4	0–15	0–15	6–26
2	0–5	0–5	0–20
1	–	–	0–5

As the sub-base will be in contact with water for a large part of the time, the strength and durability of aggregate particles when saturated and subject to wetting and drying should be assessed. The materials should also not crush or degrade, either during construction or in service. The specification of LA test values, micro deval tests and flakiness tests will address these issues. Sub-base aggregate specification requirements are summarised in **Table 20.14**. This table is from BS 7533-13:2009 for CBPP but should be applied to sub-base materials used below all types of surfacing and also for Type 3 material and for recycled materials. Note that these durability requirements are as, if not more, important than the grading and should not be ignored.

Recycled material can be used where a source is conveniently available but care should be taken that this is of consistent quality, has an appropriate grading and is free of unacceptable materials such as organic matter or steel scrap. Leachate from crushed concrete sub-base material is likely to have a high pH value, which could impede vegetation growth and thus lead to soil erosion at the drain outlet and/or cause the growth of precipitates at the drain outlet. Therefore, outlets from recycled concrete sub-bases below pervious surfaces should be designed to minimise blockage by having a large surface area through which water is collected, and the outlets should be accessible to remove build-up or precipitates.

TABLE 20.14 Sub-base aggregate specification requirements (after BS 7533-13:2009)

Properties	Category to BS EN 13242:2002 or BS 12620:2002
Grading	Grading 4/40, Gc 85-15, GTc 20/17.5
Fines content	f4
Shape	FI_{20}
Resistance to fragmentation	LA_{30}
Durability: ▪ water absorption to BS EN 1097-6:2000, Clause 7 ▪ for WA.2%, magnesium sulphate soundness	 WA242 MS_{18}
Resistance to wear	MDE_{20}
Acid-soluble sulphate content: ▪ aggregates other than air-cooled blast-furnace slag ▪ air-cooled blast-furnace slag	 AS0.2 AS1.0
Total sulphur: ▪ aggregates other than air-cooled blast-furnace slag ▪ air-cooled blast-furnace slag	 ≤ 1% by mass ≤ 2% by mass
Volume stability of blast-furnace and steel slags: ▪ air-cooled blast-furnace slag ▪ steel slag	 Free from dicalcium silicate and iron disintegration (BS EN 13242:2002, 6.4.2.2) V5
Leaching of contaminants	Blast furnace slag and other recycled materials should meet the requirements of the Environment Agency Waste Acceptance Criteria (WAC) for inert waste when leachate tested in accordance with BS EN 12457-3:2002

Note that both the resistance to wear and resistance to fragmentation are important. The LA test is an indication of the resistance to fragmentation and can only be carried out on dry aggregate. The Micro-Deval test (MD test) measures the resistance to abrasion when interlocking particles are subject to repeated loading in the presence of water which is an important property for sub-bases below pervious pavements.

Impermeable membrane characteristics

These are typically manufactured from high density polyethylene (HDPE), polypropylene or ethylene propylene diene monomer rubber (EPDM) and should be:

- durable, robust and able to withstand construction and operational loads
- resistant to puncture, multi-axial stresses and strains associated with movement and environmental stress cracking (or protected by geotextile or sand layers above and below as required – the greatest risk of puncture is often from the sub-base material laid on top of the membranes)
- unaffected by potential pollutants
- installed with fully watertight joints and discharge outlets. Welded joints should be tested to ensure the integrity of the system and provide a more robust jointing method. The membrane should be able to resist the punching stresses caused by sharp points of contact from the aggregate sub-base. It should also have sufficient strength to resist the imposed tensile forces from traffic or other loading. Where the risks associated with puncture are particularly high, consideration can be given to protecting membranes with geotextile fleeces.

▶ Further guidance on geomembranes and geotextiles is given in **Chapter 30**.

Porous asphalt

Example specification requirements for porous asphalt are provided by Korkealaakso (2014).

The surface infiltration rate (or permeability) for porous asphalt quoted by Korkealaakso (2014) are based on measurement using the test method described in Series 900 of DfT (1998). However, it is recommended that for consistency in future, the surface permeability of porous asphalt is measured using the same method as porous concrete from ASTM C1701M-09, although the specification limits would require amending to reflect the different test method.

Porous concrete

A specification for porous concrete is provided by CRMCA (2009).

The key requirements are:

- compressive strength – specified by pavement designer, typically between 3 MPa and 27 MPa (FHA, 2012)
- cement content 267–326 kg/m^3
- porosity 15–25%
- water:cement ratio 0.26–0.35.

Also to the requirements in the CRMCA specification it is recommended that the surface infiltration rate is a minimum of 250 mm/h when measured in accordance with ASTM C1701M-09.

20.12 LANDSCAPE DESIGN AND PLANTING

Permeable pavements do not often support vegetation as part of the surfacing (except for grass reinforced pavements), but the landscape can be designed and integrated either around the edge of pavement systems, or in zones within the pavement surface layout.

If trees or woody shrubs are desired, they should be carefully selected. If trees and shrubs are planted close to permeable paving it may require more regular sweeping to maintain the surface infiltration rate, although this is not likely to be excessive.

Permeable pavements are an excellent form of construction near trees, because they allow air and water to enter the soil, which is beneficial to tree growth. If tree roots have sufficient water and air in the soil, they are unlikely to damage the permeable pavement construction.

Where grass is an intrinsic part of the porous surface (eg **Figure 20.8**), it should be established before trafficking, and the surface should be kept free of sediment until the grass is established. The choice of grass is important, and it should have a high tolerance to wear and drought, and a low tendency to thatch build-up (for planting guidance, see **Chapter 29**). Where reinforced grass is used, it is important to make sure that the infill soil is lower than the grids.

Wherever possible, it is suggested that areas in and around pervious pavements should have a topsoil level that is at least 50 mm below the top of the kerb adjacent to the pervious pavement. Preferably, the areas should slope away from the pervious pavement (**Figure 20.27**). Where areas drain onto a pervious pavement, their surfaces should be stabilised so that the mobilisation of silt and other fine debris is minimised.

If this cannot be achieved (but there are many examples of permeable paving working satisfactorily next to standard landscapes), the risk of clogging should be minimised through more frequent sweeping regimes. The required frequency of sweeping should be established through visual monitoring of the surface, particularly following intense rainfall.

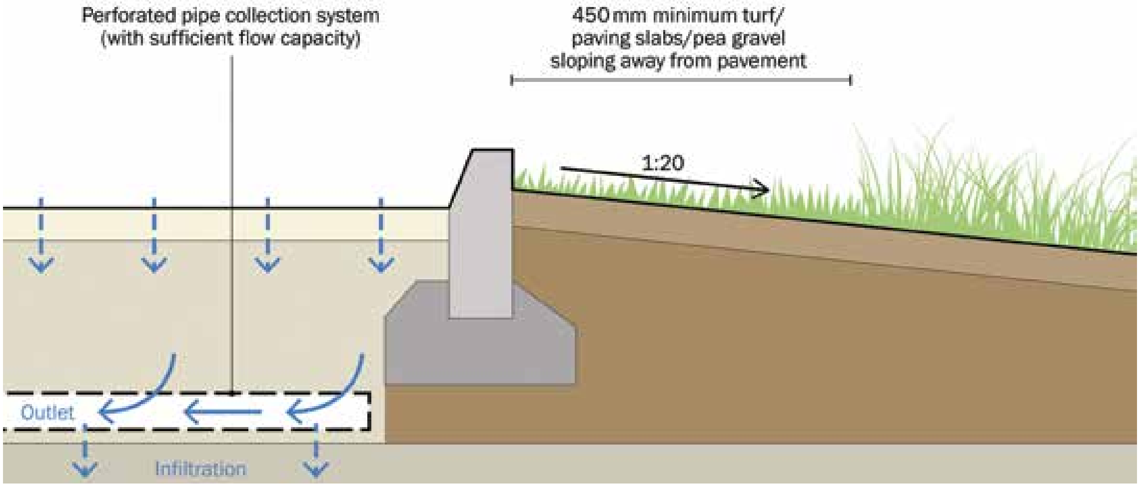


Figure 20.27 Landscape detail for pervious pavement

Figure 20.28 Hotel car park with grass-reinforced concrete blending into the surrounding landscape, Cambridgeshire (courtesy Peterborough City Council)

20.13 CONSTRUCTION REQUIREMENTS

The principles of good construction that apply to asphalt, standard concrete block paving and other impermeable surfaces generally also apply to pervious pavements. The following guidance should also be considered when constructing a pervious pavement structure. The list is in order of construction – from the subgrade upwards.

20.13.1 Subgrade

Proof rolling of the formation below Type A and B pervious pavements is not recommended as it can reduce the infiltration rate of the soil. Subgrade soft spots can be identified using a hand-held MEXEcone or similar (ie an instrument to measure *in situ* CBR values). If soft spots are identified, they should be excavated and backfilled with suitable well-compacted material and, for Type A pavements, the materials should be of similar permeability to the surrounding subgrade.

The formation should be prepared by trimming to level in accordance with DfT (1998), to a tolerance of +20 to −30 mm. If subgrade improvement is employed, testing will be needed to demonstrate that the design CBR values have been consistently achieved and, for Type A pavements, that the infiltration rate of the soil is suitable.

The formation below Type A pavements should be protected from any operations that could reduce the infiltration rate of the soil (eg heavy construction traffic, stockpiling fine materials, mixing concrete on it).

20.13.2 Geomembrane and/or geotextile

Any impermeable membrane should be correctly specified, installed and treated with care to ensure that it is not damaged during construction (**Chapter 30**).

Geotextiles should be laid in accordance with manufacturers' instructions and with overlaps between adjacent strips of 300 mm without any folds or creases. It is recommended that specialist advice be sought from the manufacturer or supplier of the geosynthetic filter (**Section 20.11.3**).

20.13.3 Capping layer and sub-base

The fines in a conventional impermeable material help to bind the different size particles together, and act to restrict the passage of water. In the case of pervious pavement materials (which lack fines), there is potential for segregation of materials during the transportation and construction process. Care should be taken to avoid segregation, but the material should be turned over by an excavator if this occurs. The risk of segregation can be minimised by using an angular, crushed material with high surface friction.

The lack of fines and the open matrix structure can result in surface movement when construction traffic passes over the sub-base, and it can be more difficult to form to the required grades. This movement can be minimised by blinding the surface with a laying course or other smaller size aggregate to fill in the voids at the surface and stabilise it. The depth of the sub-base should be adjusted to include this blinding layer.

The sub-base should be laid in 100–150 mm layers and compacted to ensure that the maximum density is achieved for the particular material type and grading, without crushing the individual particles, or reducing the porosity below the design value. There should be a tolerance of +20 to −15 mm on the design surface level of the sub-base layer. Compaction with vibrating rollers can be difficult, as it results in movement of the surface and often dead-weight rollers are more effective. Site trials are the best way to determine the appropriate compaction method.

Once laid, the sub-base should not be trafficked. This is to prevent it rutting and also to prevent it clogging with mud and other construction materials. If it has to be trafficked, it should be protected using one of the following methods:

- a layer of DBM that can then be allowed for as part of the structural design of pavement (**Section 20.9**) – this should be punctured with 75 mm diameter holes, on an orthogonal grid of 750 mm (**Figure 20.29**)
- a geotextile and sacrificial aggregate layer – removed before laying final blockwork
- for Type C pavements only, a normal capping layer for construction and then construct the pervious surface once its use as a construction surface is no longer required.

Figure 20.29 Layer of protective DBM over sub-base after coring and before laying concrete block permeable paving (courtesy Peterborough City Council)

Base

HBCGA should not be mixed in concrete mixers on site. It needs to be produced in batching plants or mixed at the quarry. Careful mixing is required because of the low cement content, and there is a need to ensure that it is evenly spread throughout the material and not segregated. Laying HBCGA should not be carried out in weather that is too hot, or in heavy rain. The guidance provided by ACPA (2011) on laying porous concrete surfacing should be followed as it is applicable to HBCGA.

Asphalt base materials should be laid in accordance with DfT (1998).

Surfacing

Generally, concrete block pavements should be constructed in accordance with current industry guidance such as that provided by UK-based manufacturer and contractor associations (eg Interpave and Interlay). Advice should be sought from the specific manufacturer on any product-specific requirements, laying and jointing materials, block patterns and block laying procedures. In accordance with good practice, the block surface layer should be fully compacted and jointed to within 1 m of the laying face at the end of each day. Other pavement surfaces should be constructed according to the relevant British Standards and/or the manufacturer’s guidance.

Once concrete blocks are laid on the screeded bedding layer they should be vibrated into the bedding layer. This causes grit to fill the lower part of the joints. Grit should be brushed into the top of the joints and the blocks vibrated again. There may be settlement of grit in the joints over the first few months of use and it is wise to allow for the blocks to be gritted again after a few months in service.

Porous concrete used as a surfacing may need joints forming in it. The ACPA recommends that the joints are not formed by saw cutting, as this leads to dust-blocking of the adjacent areas of surfacing. The joints should be formed using a “pizza cutter” roller before the concrete has set. Compaction of the porous concrete (and HBCGA) should be undertaken using rollers and not vibrating plate compactors.

Porous asphalt should be laid in accordance with DfT (1998).

Resin-bound gravel should be laid in accordance with the manufacturer’s recommendations.

For grass reinforcement systems, the bedding sand thickness should be kept to a minimum. A maximum thickness of 20 mm is recommended. It is difficult to cut grass reinforcement systems of any kind to fit complicated shapes without loss of integrity. This should be considered in the design and construction. The grass grids should not be overfilled with soil because it leads to compaction, and the grass will not grow. At least 25 mm depth should be left between the top of the grid and the infill soil. For optimum vegetation coverage the paver or grid needs to have in excess of 30% of its area available for grass growth. Concrete pavers can be heavy and may need to be machine laid. Unless product-specific skid resistance data is available, they should only be used in low-speed situations. Sometimes concrete grass grids will crack due to uneven support in the bedding sand or sub-base, but once it is cracked, the paver will bed into the sand and will usually continue to provide support to traffic. Plastic grids need expansion joints or allowance for movement in the construction as they can expand and buckle in hot weather.

Preventing soil and mud and other contaminants from entering the pavement surface, sub-base and subgrade, both during and after construction, is imperative to ensure that the pavement remains permeable throughout its design life. Construction equipment should be kept away from the area, and silt fences, staged excavation works and temporary drainage swales (which divert runoff away from the area) should all be considered to manage these risks. Landscaping activities should be carefully designed and carried out to prevent deposition of topsoil, turf and other materials on the surface of the pavement. Infiltration surfaces should not be compacted and should be protected at all times.

▶ Further detail on construction activities and the programming of construction activities is provided in **Chapter 31**.

A construction phase health and safety plan is required under the Construction (Design and Management) Regulations (CDM) 2015. This should ensure that all construction risks have been identified, eliminated, reduced and/or controlled where appropriate.

▶ Generic health and safety considerations are presented in **Chapter 36**.

20.14 OPERATION AND MAINTENANCE REQUIREMENTS

Regular inspection and maintenance is important for the effective operation of pervious pavements. Maintenance responsibility for a pervious pavement and its surrounding area should be placed with an appropriate responsible organisation. Before handing over the pavement to the client, it should be inspected for clogging, litter, weeds and water ponding, and all failures should be rectified. After handover, the pavement should be inspected regularly, preferably during and after heavy rainfall to check effective operation and to identify any areas of ponding.

Pervious pavements need to be regularly cleaned of silt and other sediments to preserve their infiltration capacity. Extensive experience suggests that sweeping once per year should be sufficient to maintain an acceptable infiltration rate on most sites. However, in some instances, more or less sweeping may be required and the frequency should be adjusted to suit site-specific circumstances and should be informed by inspection reports.

A brush and suction cleaner (which can be a lorry-mounted device or a smaller precinct sweeper) should be used for regular sweeping. Care should be taken in adjusting vacuuming equipment to avoid removal of jointing material. Any lost material should be replaced. It is also possible to clean the surface using lightweight rotating brush cleaners combined with power spraying using hot water, as shown in **Figure 20.30**. This is done every two years at the site shown.

If the surface has clogged then a more specialist sweeper with water jetting and oscillating and rotating brushes may be required, especially for porous asphalt surfaces, to restore the surface infiltration rate to an acceptable level. The specialist equipment should be adjusted so that it does not strip binder from the aggregate in the asphalt.

Figure 20.30 Deep cleaning a supermarket car park, Dundee (courtesy Abertay University)

The likely design life of grass reinforcement will be dictated by trafficking and is likely to be about 20 years if designed correctly. For concrete block permeable paving the design life should be no different from standard paving, assuming that an effective maintenance regime is in place to minimise risks of infiltration clogging. Porous asphalt will lose strength and begin to fatigue due to oxidation of the binder. This is likely to occur slightly faster in porous asphalt than normal asphalt, so the design life will be reduced slightly. Porous concrete should have a similar design life to a normal concrete slab.

The reconstruction of failed areas of concrete block pavement should be less costly and disruptive than the rehabilitation of continuous concrete or asphalt porous surfaces due to the reduced area that is likely to be affected. Materials removed from the voids or the layers below the surface may contain heavy metals and hydrocarbons and may need to be disposed of as controlled waste. Sediment testing should be carried out before disposal to confirm its classification and appropriate disposal methods.

▶ Guidance on waste management is provided in **Chapter 33**.

Table 20.15 provides guidance on the type of operational and maintenance requirements that may be appropriate. The list of actions is not exhaustive and some actions may not always be required.

Maintenance Plans and schedules should be prepared during the design phase. Specific maintenance needs of the pervious pavement should be monitored, and maintenance schedules adjusted to suit requirements.

▶ Further detail on the preparation of maintenance specifications and schedules of work is given in **Chapter 32**.

TABLE 20.15 Operation and maintenance requirements for pervious pavements

Maintenance schedule	Required action	Typical frequency
Regular maintenance	Brushing and vacuuming (standard cosmetic sweep over whole surface)	Once a year, after autumn leaf fall, or reduced frequency as required, based on site-specific observations of clogging or manufacturer's recommendations – pay particular attention to areas where water runs onto pervious surface from adjacent impermeable areas as this area is most likely to collect the most sediment
Occasional maintenance	Stabilise and mow contributing and adjacent areas	As required
	Removal of weeds or management using glyphospate applied directly into the weeds by an applicator rather than spraying	As required – once per year on less frequently used pavements
Remedial Actions	Remediate any landscaping which, through vegetation maintenance or soil slip, has been raised to within 50 mm of the level of the paving	As required
	Remedial work to any depressions, rutting and cracked or broken blocks considered detrimental to the structural performance or a hazard to users, and replace lost jointing material	As required
	Rehabilitation of surface and upper substructure by remedial sweeping	Every 10 to 15 years or as required (if infiltration performance is reduced due to significant clogging)
Monitoring	Initial inspection	Monthly for three months after installation
	Inspect for evidence of poor operation and/or weed growth – if required, take remedial action	Three-monthly, 48 h after large storms in first six months
	Inspect silt accumulation rates and establish appropriate brushing frequencies	Annually
	Monitor inspection chambers	Annually

Many of the specific maintenance activities for pervious pavements can be undertaken as part of a general site cleaning contract (many car parks or roads are swept to remove litter and for visual reasons to keep them tidy) and therefore, if litter management is already required at site, this should have marginal cost implications.

Generally, pervious pavements require less frequent gritting in winter to prevent ice formation. There is also less risk of ice formation after snow melt, as the melt water drains directly into the underlying sub-base and does not have chance to refreeze. A slight frost may occur more frequently on the surface of pervious pavements compared to adjacent impermeable surfaces, but this is only likely to last for a few hours. It does not happen in all installations and, if necessary, this can be dealt with by application of salt. It is not likely to pose a hazard to vehicle movements.

▶ Generic health and safety guidance is presented in **Chapter 36**.

CDM 2015 requires designers to ensure that all maintenance risks have been identified, eliminated, reduced and/or controlled where appropriate. This information will be required as part of the health and safety file.

20.15 REFERENCES

ACI (2010) *Report on pervious concrete*, ACI 522R-10, ACI Committee 522, American Concrete Institute, Farmington Hills, MI, USA (ISBN: 978-0-87031-364-6)

ACPA (2011) *PerviousPave, background, purpose, assumptions and equations,* American Concrete Pavement Association, Rosemont, IL, USA. Go to: **www.acpa.org/PerviousPave/About%20PerviousPave.pdf**

BEAN, E Z, HUNT, W F and BIDELSPACH, D A (2007) "Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts" *Journal of Irrigation and Drainage Engineering*, vol 133, 6, American Society of Civil Engineers, Reston, VA, USA, pp 583–592

BEECHAM, S, LUCKE, T and MYERS, B (2010) "Designing porous and permeable pavements for stormwater harvesting and re-use". In: *Proc first int European congress of the International Association for Hydro-Environment Engineering and Research*, 4–6 May 2010, Edinburgh, Scotland

BEELDENS, A and HERRIER, G (2006) "Water pervious pavement blocks: the Belgian experience". In: *Proc eighth int conf on concrete block paving*, 6–8 November 2006, San Francisco, California USA. Go to: **www.sept.org/techpapers/1293.pdf**

BORGWARDT, S (2006) "Long-term *in-situ* infiltration performance of permeable concrete block pavement". In: *Proc of the eighth int conf on concrete block paving*, 6–8 November 2006, San Francisco, California USA. Go to: **www.icpi.org/sites/default/files/techpapers/1303.pdf**

BRATTEBO, B O and BOOTH, D B (2003) "Long term stormwater quantity and quality performance of permeable pavement systems" *Water Research*, vol 37, 18, Elsevier BV, UK, pp 4369–4376

CEDERGREN, H R (1974) *Drainage of highway and airfield pavements*, John Wiley & Sons, London, UK (ISBN: 978-0-47114-181-5)

CHADDOCK, B and JONES, C R (2007) *Structural design and pilot-scale trials of modular cellular paving for greened safe havens and emergency access routes*, Transport Research Laboratory, Berkshire, UK (ISBN: 978-1-84608-850-0). Go to: **http://tinyurl.com/p6h93xl**

CHADDOCK, B and NUNN, B (2010) *A pilot scale trial of reservoir pavements for drainage attenuation*, PPR 482, Transport Research Laboratory, Berkshire, UK (ISBN: 978-1-84608-952-7). Go to: **http://tinyurl.com/ovhmbgo**

CHOPRA, M, WANIELISTA, M, STUART, E, HARDIN, M and JUJ, I (2011) *Pervious pavements – installation, operation and strength. Part 2: porous asphalt systems*, Florida Department of Transportation, Florida, USA

COLLINS, K A, HUNT, W F and HATHAWAY, J M (2008) "Hydrologic and water quality evaluation of four permeable pavements in North Carolina, USA". In: *Proc 11th int conf on urban drainage*, 31 August to 5 September 2008, Edinburgh, Scotland, UK

CRMCA (2009) *Specifiers guide for pervious concrete pavement design, version 1.2*, Colorado Ready Mixed Concrete Association, CO, USA. Go to: **http://tinyurl.com/koy9879**

DAY, G E, SMITH, D R and BOWERS, J (1981) *Runoff and pollution abatement characteristics of concrete grid pavements*, Bulletin 135, Virginia Polytechnic Institute and State University, USA

DCLG (2007) *Manual for streets*, Thomas Telford publishing, Thomas Telford Ltd, London (ISBN: 978-0-72773-501-0). Go to: **http://tinyurl.com/qd7qbgn**

DRAKE, J, BRADFORD, A AND and SETERS, T (2012) *Evaluation of permeable pavements in cold climates. Kortright Centre, Vaughan. Final report*, Toronto and Region Conservation Authority, Ontario, Canada. Go to: **http://tinyurl.com/pw8aagc**

FHA (2012) *Pervious concrete,* TechBrief, FHWA-HIF-13-006, US Department of Transport, Federal Highway Administration, Washington DC, USA. Go to: **http://tinyurl.com/qh3lc4u**

HA (1990) "A permeameter for road drainage layers". In: *Design manual for roads and bridges (DMRB)*, vol 4, Section 2, HA 41/90, Highways Agency, London, UK. Go to: **http://tinyurl.com/nfdu66h**

HA (2009) *Design guidance for road pavement foundations,* Draft HD25, Interim Advice Note 73/06 Revision 1, Highways Agency, London, UK. Go to: **http://tinyurl.com/p3yq6lv**

DfT (1998) *Manual of contract documents for highway works, Volume 1 Specification for highway works*, HMSO, London, UK (ISBN: 978-0-11552-705-0). Go to: **www.standardsforhighways.co.uk/mchw/vol1/**

ICPI (2011) *Permeable interlocking concrete pavements, fourth edition*, Interlocking Concrete Pavement Institute, Virginia, USA (ISBN: 978-1-45078-440-5). Go to: **www.icpi.org/node/2962**

INTERPAVE (2007) *The performance of geotextiles in concrete block permeable pavements, literature review*, Interpave, Leicester, UK. Go to: **www.paving.org.uk/commercial/research.php**

INTERPAVE (2010) *Permeable pavements. Guide to the design, construction and maintenance of concrete block permeable pavements, sixth edition*, Interpave, Leicester, UK. Go to: **http://tinyurl.com/pozgxzc**

INTERPAVE (2013) *Understanding permeable paving. Guidance for designers, developers, planners and local authorities, fifth edition*, Interpave, Leicester, UK. Go to: **http://tinyurl.com/pbzz2o4**

JAMES, W and SHAHIN, R (1998) "Pollutants leached from pavements by acid rain". In W James (ed) *Advances in modeling the management of stormwater impacts, volume 6,* Computational Hydraulics Int., Guelph, Canada, pp 321–349

JAYASURIYA, L N N, KADURUPOKUNE, N, OTHMAN, M and JESSE, K (2007) "Contributing to the sustainable use of stormwater: the role of pervious pavements" *Water Science and Technology,* vol 56, 12, IWA Publishing, London, UK, pp 69–75

KELLAGHER, R (2013) *SuDS study summary. Interception of 5 mm of rainfall,* project report BE-030-R2, HR Wallingford, Wallingford, Oxon, UK. Go to: **http://tinyurl.com/qcyzceu**

KEVERN, J T, SCHAEFER, V R and WANG, K (2009) "Temperature behavior of pervious concrete systems" *Transportation Research Record: Journal of the Transportation Research Board*, vol 2098, Transportation Research Board of the National Academies, Washington, DC, USA, pp 94–101

KORKEALAAKSO, J, KUOSA, H, NIEMELÄINEN, E and TIKANMÄKI, M (2014) *Review of pervious pavement dimensioning, hydrological models and their parameter needs. State of the Art*, research report VTT-R-08227-13, VTT Technical Research Centre of Finland, Finland. Go to: **http://tinyurl.com/oszsyth**

KNAPTON, J (2007) *Heavy duty pavements. The structural design of heavy duty pavements for ports and other industries, edition 4*, Interpave, Leicester, UK. Go to: **http://tinyurl.com/nbr4gxx**

KNAPTON, J, MORRELL, D and SIMEUNOVICH, M (2012) "Structural design solutions for permeable pavements". In: *Proc 10th int conf on concrete block paving*, 24–26 November 2012, Shanghai, People's Republic of China, pp1–23

LAKE COUNTY FOREST PRESERVES (2003) *Permeable paver research summary*. Lake County Forest Preserves, Chicago, USA. Go to: **http://atfiles.org/files/pdf/PermPavers.PDF**

LEGGETT, D, BROWN, R, BREWER, D, STANFIELD, G AND HOLLIDAY, E (2001a) *Rainwater and greywater use in buildings. Best practice guidance*, C539, CIRIA, London, UK (ISBN: 978-0-86017-539-1). Go to: **www.ciria.org**

LEGGETT, D, BROWN, R, BREWER, D, STANFIELD, G and HOLLIDAY, E (2001b) *Rainwater and greywater use in buildings – decision making for water conservation*, PR80, CIRIA, London, UK (ISBN: 978-0-86017-880-4). Go to: **www.ciria.org**

MPA (2009) *Constructing and surfacing of parking areas including private drives,* Asphalt Applications, Asphalt Information Service, Mineral Products Association, London, UK. Go to: **http://tinyurl.com/pwy6avw**

OBLA, K H (2007) "Pervious concrete for sustainable development. Recent advances in concrete technology". In: *Proc first int conf on recent advances in concrete technology*, September 2007, National Ready Mixed Concrete Association, Washington DC, USA. Go to: **http://tinyurl.com/puygb2s**

PRATT, C J (1999) "Use of permeable, reservoir pavement constructions for stormwater treatment and storage for reuse" *Water Science and Technology*, vol 39, 5, Elsevier BV, UK, pp 145–151

PRATT, C J, MANTLE, D G and SCHOFIELD, P A (1995) "UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality" *Water Science and Technology,* vol 32, 1, Elsevier BV, UK, pp63–69

PRATT, C J, NEWMAN, A P and BOND, P C (1999) "Mineral oil biodegradation within a permeable pavement: long term observations" *Water Science Technology*, vol 39, 2, Elsevier BV, UK, pp 103–109

PRATT, C, WILSON, S and COOPER, P (2001) *Source control using constructed pervious surfaces. Hydraulic, structural and water quality performance issues*, C582, CIRIA, London (ISBN: 978-0-86017-582-7). Go to: **www.ciria.org**

POWELL, W D, POTTER, J F, MAYHEW, H C and NUNN, M E (1984) *The structural design of bituminous roads*, LR1132, Transport Research Laboratory, Berkshire, UK. Go to: **http://tinyurl.com/q35mzjk**

PUEHMEIER, T and NEWMAN, A P (2008) "Oil retaining and treating geotextile for pavement applications". In: *Proc 11th int conf on urban drainage*, 31 August to 5 September 2008, Edinburgh, Scotland, UK

RANKIN, K and BALL, J E (2004) "A review of the performance of permeable pavers". In: *Proc 2004 int conf on water sensitive urban design, WSUD2004: Cities as Catchments*, Adelaide, South Australia, pp 366–377

RUSHTON, B T (2001) "Low-impact parking lot design reduces runoff and pollutant loads" *Journal of Water Resources Planning and Management*, vol 127, 3, special issue, American Society of Civil Engineers, Reston VA, USA, pp 172–179

SHACKEL, B (2006) "Design of permeable paving subject to traffic". In: *Proc eighth int conf on concrete block paving*, 6–8 November 2006, San Francisco, California USA. Go to: **www.sept.org/techpapers/1293.pdf**

SHACKEL, B, LITZKA, J and ZIEGER, M (2000) "Loading tests of conventional and ecological concrete block paving". In: *Proc sixth int conf on concrete block paving: JIPEA World Congress 2000*, 17–21 September 2000, Keio-Plaza Intercontinental Hotel, Tokyo, Japan, pp81–89

URBAN WATERWAYS (2008) *Permeable pavement research. Research update and design implications,* NC Cooperative Extension, State University and A&T State University, North Carolina, USA. Go to: **http://tinyurl.com/bk8rvt9**

URBAN WATERWAYS (2011) *Maintaining permeable pavements,* NC Cooperative Extension, State University and A&T State University, North Carolina, USA. Go to: **http://tinyurl.com/navuult**

WANIELISTA, M and CHOPRA, M (2007) *Performance assessment of Portland Cement pervious pavement. Report 4 of 4: Performance assessment of a pervious concrete pavement used as a shoulder for an Interstate rest area parking lot, final report*, FDOT Project BD521-02, Florida Department of Transportation, Florida, USA. Go to: **http://tinyurl.com/pf7lsgu**

STATUTES

Regulations/Orders

Construction (Design and Management) Regulations (CDM) 2015

The Road Vehicles (Construction and Use) Regulations 1986 (No.1078)

The Road Vehicles (Authorisation of Special Types) (General) Order 2003 (No.1998)

British Standards

BS 1377-4:1990 *Methods of tests for soils for civil engineering purposes. Compaction-related tests*

BS 1377-9:1990 *Methods of tests for soils for civil engineering purposes. In-situ tests*

BS 7533-13:2009 *Pavements constructed with clay, natural stone or concrete pavers. Guide for the design of permeable pavements constructed with concrete paving blocks and flags, natural stone slabs and setts and clay pavers*

BS 7533-101:2015 *Pavements constructed with clay, natural stone or concrete paving units. Part 101: Code of practice for the design of pavements using modular paving units* (in press)

European Standards

BS EN 1097-6:2000 *Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption* (withdrawn)

BS EN 12457-3:2002 *Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with a high solid content and with a particle size below 4 mm (without or with size reduction)*

BS EN 13108-1:2006 *Bituminous mixtures. Material specifications. Asphalt concrete*

BS EN 13242:2002+A1:2007 *Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction*

BS EN 12620:2002+A1:2008 *Aggregates for concrete*

BS EN 14227-1:2013 *Hydraulically bound mixtures. Specifications. Cement bound granular mixtures*

USA Standards

ASTM C1701M-09 *Standard test method for infiltration rate of in place pervious concrete*

ASTM C1781M-13 *Standard test method for surface infiltration rate of permeable unit pavement systems*