# **TarmacDry®.** Design guidelines for porous/permeable pavements

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## Introduction

It is well recognised that urban development causes permanent changes in the stormwater regime and leads to larger volumes of runoff and higher peak flow rates in the drainage system. This in turn can result in an increase in the magnitude and frequency of flooding within and downstream of the urban areas. It is equally clear that urban runoff has a significant adverse impact on the quality of the watercourse to which the drainage is discharged. Many references to conference proceedings, in which the impacts have been discussed, could be sited, but two examples may suffice (e.g. Rosener et al.,[1] Marsalek and Torno,[2]).

In the UK, practices for the control of stormwater quantity and quality have been those of flow concentration in the trunk sewers and of treatment at the reclamation works for that part conveyed in combined sewers. The increased quantities of stormwater from urban development have led to hydraulic overloading of sewers or, worse, the flooding of urban surfaces and properties. The earliest attempts to control such flooding involved increasing the capacity of the drainage system by laying larger pipes or duplicating sewers. As the urban areas expand, this becomes an increasingly costly and disruptive procedure and tends simply to move the flooding problem further downstream. Such "improvements" are now widely recognised as being detrimental to the ecology, to recreational uses and to amenity value. In recent years, engineering solutions have turned towards the provision of attenuation facilities to relieve flooding problems created by urban stormwater. These methods include the enlargement of sewers serving small developments, the construction of in-pipe detention tanks to reduce the number of sewage overflows into watercourses and the establishment of flood balancing areas in or downstream of the urban area.

It is evident, in addition, that a system which rapidly conveys surface water away from impervious areas can reduce local soil moisture recharge and lead to lowering of the groundwater table. This may have serious environmental and economic consequences with respect to the maintenance of green space and aquatic habitats in urban areas and increase the risk of soil consolidation and subsidence. Whilst the effect may partly be balanced by leakage from the urban piped water distribution system and infiltration from the sewerage system, such a reduction in water resources must be considered to be

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unsustainable in the long-term. There is thus a growing view that the best practicable environmental option should include the control of runoff at source, by employing methods which hold rainwater where it falls and which preserve the intrinsic water balance of the local area.

Porous and permeable pavement constructions are one approach to achieve this and have the merit that they do not require additional urban land for their location. Rather they may replace traditional impervious footways, highways and paved areas, generally, and hence these parts of the urban infrastructure have the dual purposes of being highway and stormwater management facilities.

## Experience with porous/permeable pavement constructions

It is helpful to define both porous and permeable pavements distinctly, as the method of construction, maintenance and operating life may be different for each of them.

A porous pavement construction is surfaced with materials which allow the immediate infiltration of rainfall into the underlying construction across the total surface of the pavement. Examples of these surfacing materials are porous macadam and no-fines, concrete block paving i.e. the stormwater flows through interconnected pores within the surfacing material. On the other hand, a permeable pavement is surfaced with materials which are not themselves porous, but which provide inlets in the surface to allow the stormwater to enter the underlying construction. An example of such surfacing is grass-concrete blocks, which form a lattice of holes surrounded by pressed concrete and offering an open area for grass to grow and water to enter of around 80% of the top surface area. Both porous and permeable surfacing may be described generally as pervious materials.

Today, probably the most extensive use of these types of construction has been in Tokyo, where it is estimated that some 494,000m$^2$ of both porous and permeable types of pavement have been constructed since 1984, [Fujita,[3]]. The main impetus for their use and for other forms of local stormwater management in the City was the need to reduce the peak flows in the urban channelised rivers, where flooding in the densely populated areas was causing enormous damage and threat to life. Apart from achieving the required very significant decreases in river flows, other benefits which have been claimed for the adoption of local stormwater management techniques are the raising of groundwater levels and the reduction of ground settlement; conservation of the urban ecology, especially trees; moderation of temperatures in the urban districts by local evaporative cooling and the recovery of base flows in the alluvial rivers in the urban district [Fujita,[4]].

Whilst no other country can show such a concentrated application of porous/permeable pavement constructions as in Tokyo, Japan, other countries have made earlier use of

them. The USA has led the way in producing comprehensive guidance on design and maintenance [Anon,[5] Schueler,[6]] and was foremost in the early evaluation of the benefits of these pavement constructions for car parking areas [Bachtle,[7] Day et al.,[8] Diniz,[9] Goforth et al.,[10] Jackson and Ragan,[11] Smith,[12]]. More recently, researchers in European countries such as Sweden, France and the UK, have shown interest in these techniques.

In Sweden, the use of porous macadam laid on free-draining, crushed stone aggregate sub-base has been shown to offer important stormwater discharge quantity and quality benefits [Hogland et al.,[13] and[14] Larson[15]]. Used for car parking and for highways in residential developments, the 'Unit superstructure' has been claimed to produce peak flow reductions of about 80%. To reduce discharge volume by 77%-81% for all return periods, and to be up to 25% cheaper (or at the least to be no more expensive than traditional forms of pavement construction) when taking all construction and drainage costs into account (i.e. accepting that the porous macadam itself is a more expensive surfacing, the extra cost of which is offset by the savings in underground pipework etc), [Niemczynowicz and Hogland,[16] Niemczynowicz et al.,[17]]. The Swedish 'Unit Superstructure' has no impermeable membrane undersealing the sub-base, instead a geotextile is laid between the sub-base stone and the sub-grade to prevent the movement of soil into the structure, but this does not impede the flow of water into or out of the sub-base. Ground conditions in Sweden generally have been those of clay or rock, hence infiltration into the ground is somewhat limited. Water is discharged from the sub-base through drains at the low points in the sub-grade at the edge of the construction, or used by plants in the surrounding soil and transpired.

In the UK only two porous macadam-surfaced car parks are known to have been constructed, one experimental area of 200m$^2$ at Nottingham Trent University and the other of some 750m$^2$ at commercial premises in Ashby de la Zouch, Leicestershire. Both were built around 1987 and are still operating well, retaining their free-draining surface. Until 1996 there was little other use for porous/permeable surfacing for highways except that of grass-concrete blocks for emergency access roads for fire engines across grassed or landscaped areas; and of an experimental, pressed concrete block, known as the CeePy block, used to surface an infiltration trench along one side of a 6,500m$^2$ car park at Shire Hall, Reading, UK. This car park constructed in 1986, was surfaced generally with impermeable block paving and graded to fall to one side, at which a one-metre wide by two metre deep trench, filled with free-draining aggregate, was covered with the permeable CeePy block surface to intercept surface runoff. The stormwater infiltrated to groundwater. In 1992 field measurements on the cores between the CeePy blocks over the trench gave values of infiltration rate of 2,600mm/h on average, which was sufficient to ensure full interception of surface runoff under rainfall intensities of

60mm/h over the car park. This was a very satisfactory performance as the trench surfacing had not been maintained during the ten years of operation, [Pratt,[18]].

The development in the UK of the CeePy block was the result of observations that the commonly available grass-concrete blocks allowed consolidation of the soil spaces, thus leading to reduced infiltration. The CeePy block was provided with a raised disc surface profile to carry the car tyre footprint, thus avoiding the load being applied to the pattern of 50mm diameter percolation holes. Although the possibility of consolidation exists with grass-concrete products, nevertheless, they have been extensively used and monitored to determine their flow and pollution control potential.

In the USA, comparison trials were made between two similar car parking areas in the City of Dayton, Ohio: one surfaced with grass-concrete and equipped with only one gully to receive surface runoff, and the second surfaced with impermeable asphalt and drained by a number of gullies. The observations showed that runoff volume from the grass-concrete car park into the drain ranged from 0%-35% (mean value 10% for 11 storms) of the runoff from the asphalt surface, no runoff occurred from the grass-concrete for four of the eleven storms; and the storm for which the highest percentage runoff occurred was not the largest storm, but one which followed immediately a previously wet day, from which there had been no runoff (i.e. antecedent moisture conditions were important and the number of dry days between storms determined the effectiveness of the pavement to absorb stormwater [Smith,[12]].
As an example, a storm which followed twelve dry days produced only 20% runoff from the grass-concrete as compared with the asphalt surface, despite the storm being of high intensity producing peak runoff of 21.8 l/s (grass-concrete) and 223.6 l/s (asphalt).

A similar feature concerning the antecedent weather conditions was observed in the UK experiments, where it was noted that the runoff reduction was greatest for long duration storms following days of dry weather. This combination of factors allowed the concrete surfacing blocks to evaporate stored moisture from previous rainfall and a subsequent long duration storm gave time for absorption of rainfall into the blocks: up to 7mm rainfall has been stored within the blocks during long events, subsequently to evaporate.

It was previously mentioned in connection with the experience in Tokyo that local stormwater management methods could lead to moderation of temperatures in urban areas. This was also monitored in the City of Dayton where dry bulb air temperature differences of 1°C to 3°C were observed between the grass-concrete and the higher temperatures over the asphalt surface. Temperatures were in the range 24°C to 31°C over the asphalt surface. Radiometric temperatures, which are indicative of the reflected heat felt by pedestrians, were also

recorded over both surfaces. Again the grass-concrete surface gave lower readings by some 3°C to 7°C in a range from 34°C to 54°C for the asphalt surface.

As important as high temperature effects are concerns about the performance of porous or permeable pavement constructions in low or freezing temperatures. The evidence from the UK studies indicated that the air stored within such structures took five days to cool by 2°C (from 10°C to 8°C), even when air temperatures fell from 9°C to -4°C and -3°C on consecutive nights in the period [Pratt,[18]]. The UK rarely experiences prolonged freezing weather, but for short spells of cold weather the air within the pavement would act as a 'night storage heater', releasing heat to the surface to thaw frost. This advantage means that there is little need for winter salting. In southern Sweden where temperatures are lower for longer periods this property has also been noted and has avoided the problems of blockage of porous macadam surfaces with winter salt/sand mixes [Larson,[15]]. In northern Sweden at Lulea just south of the Artic Circle, temperatures are very low for long periods, but even there it has been advantageous to experiment with porous macadam-surfaced, porous pavement construction, as a means to limit frost heave of the highway. No problems occurred with the surfacing of the construction under these extreme conditions of low temperature, even with the presence of water at the sub-grade, although the traditional impermeable highway structure and pipe drainage in the same area were disrupted by heave [Stenmark,[19] and [20]].

In addition to surfacing with porous macadam or perforated concrete blocks of various designs, surfaces have been formed of porous concrete blocks [Suda et al.,[21]]; of porous slabs made from vitrified sewage sludge; and of granite setts laid with a course sand matrix [Jacobsen and Harremoes,[22]]. The porous concrete blocks were reported by Suda to have 12% void space with an infiltration rate of 360mm/h when new, however recently developed porous blocks in the UK have been measured to have a throughflow rate of some 3,500mm/h (individually) and an as-laid rate of 4,500mm/h, when joints also allow throughflow. The values may be compared with results for porous macadam for which surface infiltration rates of some 61,000mm/h, but on average about 39,000mm/h, were measured on a five year old surface in Nottingham [Pratt,[18]]. The observations on a granite sett surface showed that runoff into a gully would occur for some storms, dependent on the antecedent conditions (as observed by Smith,[12] in Dayton, Ohio), however, there were many occasions when most, if not all, the rainfall would be infiltrated between the setts (impermeable area of granite setts was 72% of surface). It was calculated that only some 9% rainfall on average flowed over the granite sett surface into a gully where inflow was monitored. Similar results were reported from Holland where study of surfacing with impermeable concrete bricks and slabs, laid with wide joints,

produced infiltration rates of 13mm/h on average, which, whilst below the rate to avoid surface ponding for heavy rainfalls, would ensure that typically some 50%-70% rainfalls drained quickly without puddles [van Dam and van de Ven,[23]].

Another advantage of porous or permeable pavement constructions is that they provide an effective means of attenuation and runoff reduction through storage within the sub-base. This result is obtained whether or not there is also volume reduction by infiltration of the stormwater into the soil at the site. Other opportunities also exist, such as control of the time and date of discharge from the pavement; and of water re-use if the stormwater inflows are stored long-term in the construction. The storage capacity of the sub-base may be 100-200mm rainfall, assuming 30% voids in the sub-base i.e. typically some two months rain for many lowland parts of the UK, hence it is possible to restrict discharge from the sub-base until some suitable time and date, in order to prevent downstream flooding, or to allow the waters to be passed to treatment without undue loading of the reclamation works, say, overnight on a Sunday when industrial and household discharges are at a minimum. There also exists the option of re-use of the waters for garden irrigation, external washing operations or toilet flushing [Schilling et al.,[24] Schofield,[25]].

If the opportunity is to be taken to re-use water stored in porous or permeable pavements, or even if it is not and concern is simply about the quality of the effluent from the construction, it is important to be aware of the water quality implications and the environmental impact of the use of these pavements. Observations in the laboratory and in the field by a number of researchers have shown that pollutants washed into pervious constructions tend to accumulate within the structure. In the case of construction with porous macadam surfacing, the pollutants have been found mainly on the geotextile at the base of the construction, with little evidence of pollutant discharge downstream or to groundwater [Hogland et al.,[14] Balades et al.,[26] Legret et al.,[27]]. Studies on full-scale laboratory models and in the field on a permeable pavement surfaced with CeePy blocks have shown that pollutants are also concentrated on the geotextile but, because of the different level in the construction at which the geotextile is located, the pollutants are retained towards the top of the construction where retrieval or treatment might be easier and less costly [Pratt,[28]].

In the UK the permeable pavement with CeePy block surfacing has the blocks laid on 50mm of 5-10mm gravel, which is placed on a geotextile over a sub-base of free-draining crushed stone. The 50mm holes in the surfacing are filled with gravel, which with the bedding gravel and the geotextile act as a filter to remove sediment from the percolating stormwater [Pratt et al.,[29] and [30]]. The permeable pavement is constructed within an impermeable membrane and stormwater is removed from the sub-base

via a drain, a design which prevents discharge to groundwater except at the drain where quality monitoring may check for any possible harmful pollutants. Water quality analyses of the drain effluent showed that the construction was providing treatment of the stormwater, such that after an initial stabilising period the effluent water quality was high (i.e. only 5-45mg/l suspended solids, < 5mg/l biological oxygen demand and chemical oxygen demand < 10mg/l. Recently, laboratory observations confirmed that bio-remediation of oil pollution may be undertaken within the pavement [Pratt et al.,[31] Pratt and Bond,[32]].

Results from two experimental rigs, one receiving a single application (0.3 $l/m^2$) and the other regular, twice weekly additions of oil (10.4 $ml/m^2$ per application up to a total of 1.2 $l/m^2$ over 440 days) and of simulated rainfalls have shown that, despite the vertical flow paths through the rigs which minimise the flow path and time of contact of oils within the construction, the percentages of oil monitored in the effluents were only 0.5% and 2.5% of the total oil applied. Both results were consistent throughout the test durations of 78 and 440 days, respectively. For the 78 day test, the oil actually degraded by micro-organisms within the rig was analysed/calculated to be between 5.7% and 7.8% of the oil applied, with 84% of the oil being retained on the internal surfaces of the construction, the majority (68%) on the geotextile. Research continues in order to investigate the construction's ability to respond consistently over long periods.

In general, the studies of the pollution retention and discharge characteristics of porous and permeable pavements have indicated that the constructions are effective at filtering sediments from stormwater, which may affect infiltration rates at the surface in time; that they provide internal sites for the retention and adsorption of pollutants, such as oils and heavy metals which may accumulate steadily over time and require careful removal when the pavement is reconstructed; and that they may be used as an aerobic bio-reactor to degrade oils and grease, given appropriate nutrients and ambient conditions to maintain a viable microbial population.

## Design implications from current experience

There are a number of aspects which must be considered in the design of pervious pavements, such as structural strength of the pavement under anticipated use; hydrological inputs, hydraulic response, and pollutional impacts, both at the pavement site and downstream on receiving waters. The structural design will vary with the expected loadings on the pavement from people and vehicles; its expected operating life, and the 'quality' of the location, which may impose performance criteria, such as limits on the differential settlements across the pavement. In general, higher structural design specifications tend to lead to greater construction depths, requiring additional materials, with consequent increase in internal void space. Hydrological and hydraulic design is only in part dependent upon usage (e.g. when

the pavement is to store stormwater for re-use purposes), but is principally dependent upon the local climatic factors and on the effluent discharge criteria. Clearly the pollution control design will be affected by the hydrology and hydraulic design criteria, with major importance being placed upon discharge criteria. Discharge quality depends upon inputs to the pavements, so usage and the local environment from which pollutants are derived and which may deposit on the surface of the pavement must influence design. Discharge of stormwater through the base of the construction, of whatever quality, may adversely affect the bearing capacity of the underlying subgrade and so lead to structural design implications.

From the above, it is clear that design is a compromise, especially with pervious pavements, as structural, hydrologic, hydraulic and pollution aspects all affect each other in some way or other. The aspects are inter-related and the importance of every one of them must be assessed on a location-by-location basis. Hence it is possible to list factors to be considered but not to place them in any priority order. What pervious pavements have to offer is a flexibility of final design which allows for their usage under a very wide range of operational and environmental conditions. Where experience has shown that difficulties arise is in the prediction/achievement of the design life of the pavement and of instituting the appropriate maintenance to achieve that design life.

Structural design failures do occur but, more commonly, it has been unsatisfactory performance in the interception and infiltration of stormwater because of blockage of the top surface which has caused ‘failure’. Such failure is due to:

- changed or poorly assessed usage of the pavement, leading to:
  - compaction of the surface due to increased loadings, reducing the infiltration
  - increased deposits blocking inlets in the surface of the pavement
  - changed or poorly assessed environmental conditions in the vicinity of the pavement causing:
    - increased deposits
    - inputs of pollutants which affect infiltration (e.g. nutrients enhancing weed growth)

- changes in the maintenance performed or of its effectiveness, resulting in:
  - accumulating deposits on and in the top surface
  - decreasing inflow rates through the top surface

Whilst it is not easy to predict and plan for some of these changes, it is possible to maximise the operational life of pervious

## Pavement elements

### Surface Design:

Permeable and porous pavements require different criteria for their surface design and for their maintenance. The demands of porous surfaces are far higher than are those of permeable type surfaces, because failure usually results in the reconstruction of the surface after the complete removal of failed sections. Failure of porous surfaces involves the internal blockage of the pores, which eventually cannot be cleaned by either vacuum or jetting processes. On the other hand, permeable surfaces fail through the reduction in the rate of percolation through the inlets in the surface. Remedial works usually involve the lifting and re-bedding of the surface blocks or of the excavation of the material in the inlets and its replacement with appropriate, new free-draining media.

| Pavement Type | Design | Maintenance |
|---|---|---|
| **Permeable**<br>• Lattice block, grass-concrete etc | Ensure loading on surface does not compact deposits in inlets through surface, i.e. restrict size of inlets and provide load bearing surfaces | Regular, stiff brushing and removal of loose deposits |
| **Porous**<br>• Macadam, no-fines concrete, etc | Optimise the number and size of infiltration pores per unit surface area to maintain an open matrix for throughflow | Frequent, vacuum/jetting of surface to remove loose deposits and clear pores |

The merit of porous surfaces over permeable areas is that, in general they have even, smooth surfaces which are more comfortable to walk upon or to push small-wheeled trolleys over.

### Layout Design:

For both porous and permeable surfaces, the area draining stormwater through the surface of the pavement may be larger than the pavement surface area i.e. adjacent paved areas and roofs may discharge onto the pavement, however such additional discharge will require that maintenance be enhanced to limit the transport and deposition of material from impermeable surfaces over the porous/permeable surface.

The environment surrounding the pavement may be a source of material likely to block the surface of the pavement. Landscape areas should be separated by a kerb face, at the minimum, such that soil and plant debris cannot be washed or blown onto the pavement. Seasonal leaf litter will need to be collected as part of planned maintenance. Since one advantage of these pavements is pavements

their opportunity to store water for re-use for landscape irrigation, tress and shrubs which enhance the urban area, can benefit from being adjacent to these pavements, given that appropriate maintenance is instituted. In the UK it has been recommended that pervious pavements be constructed on top of the subgrade surface, rather than within it, where there are existing mature trees. Such an approach avoids damaging the roots during construction work and the pavement continues to supply water to the underlying subgrade for tree use, which is not achieved with impermeable constructions[33].

**Contour Design:**
Pervious pavements are most effective at stormwater interception when they are constructed with a horizontal top surface. Streams on the surface due to grading inevitably concentrate debris along the flow path. Where grading is unavoidable every effort should be made to encourage sheet flow, in order to minimise the depth of flow and maximise its width, thus minimising velocity and the transport capability of the flow to move debris over the surface to low spots.

Where low spots are formed on the pavement, it may be advantageous to provide gully inlets to intercept flows and prevent surface ponding or unwanted off-site discharge which may flood adjacent land. Off-site discharge should be controlled by establishing a containing wall (e.g. kerb) or bank around the pavement. Such containment need only be a few tens of millimetres high. At a vehicle entrance to a pavement a gentle ramp on the surface may be used to form the containment and prevent off-site discharge. The purpose of the containment is to provide surface storage for stormwater during any storm period, when infiltration to the pavement falls below the rainfall input. After some years of operation with deposits in the surface of the pavement, the use of the surface storage will be increasingly called upon, however the depth of surface flooding and its period of existence will be limited, but gradually increase, until failure of the surface is declared to have occurred, when there is prolonged surface ponding.

It is only possible to predict approximately the operational life of these pavements, as the environmental factors vary from site to site. As an indicator, the Shire Hall, Reading, UK permeable pavement site, detailed previously [Pratt[18]] has operated satisfactorily for 11 years without maintenance. After 6 years, infiltration rates were still high despite draining an impermeable area some 30 times larger than the permeable surface and being surrounded by shrubs and trees. Such a layout is far from ideal, but it appears to have performed well and, given maintenance in the future, could continue so to do for many years. The best estimate of operating life with limited maintenance, based upon present experience of the CeePy surfaced permeable pavements, is 15 years. After that time it might be necessary to renew some of the gravel in the inlets in the pavement surface as they become blocked by silt.

**Internal Pavement Structure:**
Three considerations influence the design of the internal structure:

- the surfacing materials
- the pollution retention strategy and
- the stormwater retention/detention aspects of the pavement

Permeable pavements with concrete units forming a latticework surfacing are usually bedded upon sand or gravel. In the case of 'temporary' or low usage permeable pavements this surfacing is placed directly on the soil without further structural layers. Such pavements offer local stormwater management through infiltration to groundwater and pollution retention in the bedding material and upper soil horizon. Because such surfaces often have grass growing in the lattice inlets, intentionally or not which reduces infiltration rates, it is important that either excess surface water can discharge from the pavement into adjacent swales or gully inlets, or be retained on the surface as a result of the contouring of the surface, until infiltration is complete.

When usage and/or loadings are high, it is necessary for pervious pavements to be laid over a crushed stone sub-base. Porous macadam is usually laid on a crushed stone levelling course (10-20mm diameter, 50-100mm thick) which overlies the crushed stone sub-base (10-150mm diameter). It has not been usual to install a geotextile layer between the levelling course and the sub-base stone and so sediment and pollutants have usually progressed downwards to the base of the construction, as reported by Legret et al.,[27]. Pavements with block-type surfacing usually have the blocks laid on sand or gravel which is separated from the sub-base stone by a geotextile layer.

Dependent upon whether the stormwater entering the construction is to discharge to groundwater or be collected in a sub-base drain, the base of pervious pavements will have either a second geotextile layer or an impermeable membrane separating the construction from the subgrade. The thickness of the sub-base layer will usually be designed to suit the structural strength criteria, but it may be increased to provide additional storage volume for re-use water or to compensate for ground contours to provide a desired finished surface profile.

In pollution retention terms it is advantageous to maximise the filtration, sedimentation and adsorption processes which occur within the pavement construction. Where stormwater is filtered by a geotextile, the sediments in the effluent have been found to be principally derived from the internal materials of the construction below the geotextile [Pratt,[28]]. Also as oils seem to be predominantly retained on the geotextile, as shown by laboratory experiment [Pratt and Bond[32]], it seems advisable to specify the inclusion of a geotextile layer within the top 100-200mm of all pavement types.

**Discharge Design:**
Four forms of discharge may be designed for these pavements:

- vertical infiltration to groundwater through the base of the construction
- or with a sealed base to the construction:
  - uncontrolled sub-base drain discharge off-site
  - controlled drain discharge, possibly under real time control
  - no off-site discharge and internal storage of stormwater for re-use as garden irrigation waters, for toilet flushing, etc.

In all cases when there is discharge other than to groundwater, it should be at a slow rate of release. This will occur if control is imposed at the outfall, or the internal flow paths to the outfall are maximised in order to achieve significant attenuation of the outflow hydrograph. This increase in flow path may be achieved in a variety of ways but one, which is convenient when using 4m wide rolls of impermeable membrane to underseal the construction, is to lay the membrane along the contour and raise the side edges to form a trough-type containment for the sub-base stone. Adjacent troughs are interconnected at each end of the contour so that stormwater flows along the full width of the contour before entering the next downslope trough, where again it must flow back across the full width of the contour before entering the next downstream trough. Such an interconnecting system of sub-base panels within the construction prevents the rapid flow of stormwater downslope with possible surface flooding potential at the low points.

On sites where the ground slopes and the base of the construction is not sealed it may be useful to construct infiltration trenches along the contour within the construction, so that downslope flows within the construction are intercepted by a trench until full, before any progress downslope continues.

The option of using the pavement construction for water storage is now being considered in the UK. At one location the sealed construction is being used to store both pavement and roof waters for subsequent re-use for toilet flushing [Pratt,[34]]. With the increase cost of treated water and with some summer shortages of supply in parts of the UK, interest is growing in local storage for re-use. To increase the volume of storage, it may be advantageous to increase the depth of the sub-base.

## Outline design criteria

Structural design criteria will be set to ensure the strength of the pavement and of the underlying subgrade to carry and transmit the anticipated loadings. When the pavement discharges to groundwater there is the possibility of changes in bearing capacity of the soil with time.

Hydrologic and hydraulic criteria will define the design rainfalls and the acceptable discharge conditions. If the surface, contour and layout

designs incorporate the containment of surface waters to account for surface infiltration rate reductions over time, it should not be difficult to ensure acceptable performance for many years before any reconstruction work is necessary. Since porous and permeable surfacing materials initially have high and sometimes very high infiltration rates of flow, absolute values of design rainfall are of less significance than the maintenance schedules for the pavement surface. Design rainfall intensities of 50 or 100mm/h are insignificant in comparison with surface infiltration rates of 10000mm/h or the like, until silt blockage of the surface brings these parameters to similar order of magnitude after several years. Hence it is the surface storage components which become critical in the long term.

Similarly, the soil infiltration rate at the base of the construction is not always significant in relation to the inflow rate, as the internal storage capacity of the construction provides sufficient retention for the slow release of waters before any danger of surface flooding exists. Similarly, where sub-base drains are used to convey stormwater from the construction, any deficiency in capacity is easily accommodated by the void space within the sub-base.

The local climatic conditions must be considered within the design procedures for pervious pavement, but the in-built safety of operation which can be achieved with porous and permeable pavements through thoughtful selection of pavement, contour, layout, internal structure and discharge elements can make the application of sophisticated design procedures unnecessary. The effects on performance of poor selection of these elements and poor maintenance far exceed the effect of a mis-selection of design rainfall intensity on the design.

## Defintions of failure of a porous/ permeable pavement

Design is not usually a process in which the timescale to failure is of primary importance, but with pervious pavements failure must be expected to occur eventually and time to failure is an important consideration. The influence of environmental and maintenance aspects, which principally control design life, is not well defined and experience with pervious pavements is poorly recorded to assist in this respect.

Structural failure may be defined in relation to the rutting depth on the surface or of differential settlement across the pavement. Structural failure is usually clear to see and to measure against a criterion and exists to see from one day to the next. Hydraulic failure on the other hand may be related to the duration of surface flooding or the depth of standing water, spasmodically. Or, instead of hydraulic failure at input, hydraulic failure may be related to downstream discharge in excess of permissible criterion. Similarly, transient pollutional problems may define the failure condition. There is a very real difficulty in assessing the failure of pervious pavements in

hydraulics and probably in pollutional terms as well, because the occurrence defined as failure may be transient, may be irregular in its appearance and the cause of failure may even improve through natural processes or as a result of maintenance. Also the perception of failure in the observers may change with time. A few millimetres of water standing on the surface for a few minutes may be described as a failure when it first occurs, but if such standing water flows away quickly, leaving no damage and causing little or no disturbance, it ceases to be seen as a problem. The perception of the observer of what rates as failure is modified. At this time there seems more concern, at least in the UK, not to chance failure occurring than to grasp the many advantages of these pavements in terms of flow attenuation and pollution control for a design life of 15 to 30 years, say, before 'failure' is defined.

## Conclusions

The experiences derived from porous and permeable pavements over the last twenty years or so have indicated several important benefits from their installation, but also revealed their sensitivity to environmental factors and changes over time, both on the pavement itself and in the locality. The paper has drawn together some of the experiences and suggested how they lead to a set of design recommendations for the elements of the pavement which maximise the advantages, whilst recognising that 'failure' by some definition is an eventual occurrence. The aim of the maintenance-free porous/permeable pavement is a dream, as is the maintenance-free traditional pipe drainage system. The reality is that pervious pavements can provide some or all of the benefits of flow attenuation; aquifer recharge, pollution control and treatment, stored water re-use, and effluent quality enhancement for one, two or more decades.

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