GUIDELINES FOR PERMEABLE INTERLOCKING CONCRETE PAVEMENTS (PICP) IN SOUTH AFRICA

Neil Armitage & Motlatsi Monyake

Volume 2: Guidelines for the Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement (PICP) in South Africa

WATER RESEARCH COMMISSION

TT 913/2/23

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Volume 2

Guidelines for the Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement (PICP) in South Africa

Report to the
WATER RESEARCH COMMISSION

by

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This report forms part of a set of two reports. The other report is *Guidelines for Permeable Interlocking Concrete Pavements (PICP) in South Africa. Volume 1: Clogging in Permeable Interlocking Concrete Pavement (PICP)* (WRC Report No. TT 913/1/23).

Preface

Rapid urbanisation since the commencement of the industrial age has resulted in much land becoming impervious owing to the construction of roads, parking lots, driveways, and buildings. This has resulted in an increase in stormwater runoff and a corresponding decrease in infiltration. The traditional approach to urban drainage in South Africa is to convey stormwater runoff in pipe and canal networks to the nearest receiving water bodies as quickly as possible. This, however, leads to increased runoff velocities and volumes resulting in the erosion and consequent siltation of watercourses whilst stormwater pollutants – such as heavy metals, hydrocarbons from motor vehicles, faecal matter from inadequate or failing sanitation, and nutrients such as nitrogen and phosphorus – cause a deterioration in the water quality. There has been reduced groundwater recharge leading to the dropping of the water table in some areas.

In many countries, including South Africa, a more sustainable approach for stormwater management termed, *inter alia*, Sustainable Drainage Systems (SuDS) has been increasingly adopted in recent years to mitigate the potential damage from stormwater. As one of the source controls in SuDS, Permeable Pavement Systems (PPS) offer a potential solution to the problem of increased surface runoff and decreased stream water quality by promoting the infiltration of stormwater runoff through the wearing course into the underlying aggregate layers prior to infiltration and/or downstream discharge. The aggregates act as a filter affording some treatment. PPS can be adapted to make an effective stormwater harvesting and storage device for fit-for-purpose water re-use. Alternatively, the stormwater could be used to enhance groundwater supplies. Even if the stormwater ultimately drains from the site, the flow rates will have been massively reduced and the water quality improved.

Permeable Interlocking Concrete Pavements (PICP) are the most widely used PPS both internationally and in South Africa – with the first example in South Africa being constructed in 2008. Unfortunately, despite the increasing experience of PICP construction in South Africa and a growing international body of expertise including the development of both British (BS 7533-13:2009) and American (ASCE/T&DI/ICPI 68-18) Standards, infiltration tests carried out between 2017 and 2022 at numerous sites in Cape Town, Ekurhuleni, Johannesburg and Pietermaritzburg showed that nearly everyone was either clogged or nearly clogged, i.e. the so-called permeable paving had ceased to be permeable. The purpose of these guidelines is to help ensure that future PICP installations will be more successful with fewer failures. They are intended as a 'living document' that will be updated from time to time in the light of increasing experience in the use of PICP in South Africa.

Acknowledgments

The compilation of these guidelines was guided by an extensive working group comprising, *inter alia*, of academics, students, representatives of local authorities, consultants and suppliers. Funding was made available by the Water Research Commission of South Africa (WRC). A list of key contributors follows.

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Glossary

AASHTO	American Association of State Highway and Transport Officials
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing Materials
Basecourse	The aggregate layer of the pavement section below the bedding layer but above the subbase and/or subgrade
Bedding layer	The aggregate layer supporting the pavers; usually 7.1 mm roadstone
CMAA	Concrete and Masonry Association of Australia
Edge restraint	An edging feature, such as a concrete strip, to prevent the paving from lateral movement
Full infiltration PICP	A PICP designed to infiltrate all the rainfall into the subgrade.
Geomembrane	A liner that prevents the movement of water into the subgrade
Geosynthetic	Synthetic products used to stabilise terrain or pavement layers
Geotextile	A planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted or woven, used in contact with soil/rock and/or any other geotechnical material in civil engineering applications. They are used to separate different material layers and can also contribute to the reinforcement of the system and potentially the treatment of stormwater.
Gritstone	The rounded 5 mm Grade 1 roadstone used in the paver joints
Herringbone pattern	A laying pattern that results in pavers orientated at 90˚ to each other
ICPI	Interlocking Concrete Pavement Institute (USA)
LCCA	Life Cycle Cost Analysis – a tool to assess the cost of an installation over its entire design life
Mod-ASTM	Modified ASTM C1781 Single-Ring Infiltration Test
Mod-SWIFT	Modified Stormwater Infiltration Field Test
No infiltration PICP	A PICP that does not allow rainfall to infiltrate the subgrade, instead routing it out through an underdrain
Partial infiltration PICP	A PICP that only infiltrates a portion of the rainfall into the subgrade before discharging the rest through an underdrain
Permeability	The rate at which fluid passes through a porous medium
PICP	Permeable Interlocking Concrete Pavement
Porosity	The volume of voids in the pavement layers divided by the gross volume of the layers

Run-on Factor (RoF)	The ratio of impermeable area to the permeable area draining it
SANS	South African National Standards
SAPEM	South African Pavement Engineering Manual
SCM	Stormwater Control Measure
Single sized aggregate	Grade 1 roadstone aggregates to SANS 1200 M:1996 Table 1 and SANS 3001-AG1:2014. While these would mainly comprise stone passing the nominal ‘single size’ and retained on the immediately smaller sieve size, limited percentages of other sized aggregates are allowed in accordance with the given standards
Subbase	The lowest part of a pavement section, usually characterised by the largest aggregate
SuDS	Sustainable Drainage Systems
Subgrade	The founding soil on which the pavement structure is constructed
T&DI	Transportation and Development Institute of the ASCE

1. Introduction

This document serves as a guideline for the design, construction and maintenance of Permeable Interlocking Concrete Pavement (PICP) for South African conditions. It should be read in conjunction with the latest edition of the American Society of Civil Engineering (ASCE) Standard for Permeable Interlocking Concrete Pavement (ASCE/T&DI/ICPI 68-18 at the time of preparation of this document). Additional guidance is available from the latest edition of the (US) Interlocking Concrete Pavement Institute ® ICPI Tech Spec 18. PICP is a permeable pavement structure that comprises concrete pavers with vertical slots packed with 'gritstone' (termed 'joints') placed upon a single-sized stone bedding that is, in turn, laid upon single-sized stone basecourse and (potentially) subbase layers. Geosynthetics may be placed under the bedding and/or subbase layers, while the PICP may be equipped with underdrains in areas of low permeability or where infiltrated water could be a threat (Figure 1).

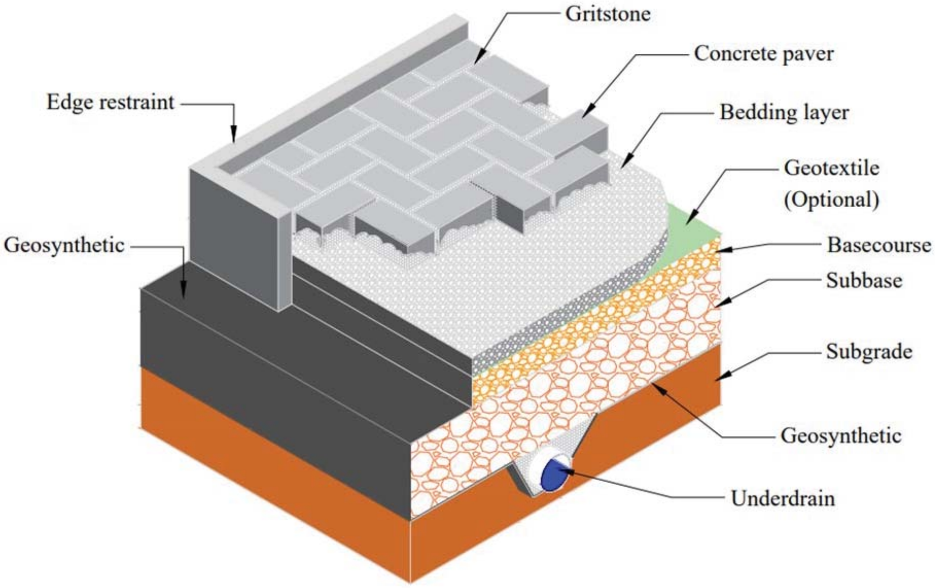


Figure 1: Typical PICP section (After ICPI, 2020)

PICP is particularly useful where site constraints prevent the use of simpler, cheaper SuDS interventions such as bioretention cells (see, e.g., The South African Guidelines for Sustainable Drainage Systems (Armitage *et al*., 2013) for more information on alternatives to PICP). This document covers the three distinct phases involved in PICP systems:

i) Design

ii) Construction

iii) Maintenance

2. PICP Design

2.1 Introduction

2.1.1 PICP is a SuDS Stormwater Control Measure (SCM) that may be used in place of conventional road, parking area or walkway surfaces. It facilitates the management of both stormwater flow and quality by absorbing surface runoff and processing it through various aggregate layers. It can lead to considerable savings in stormwater management if correctly designed, constructed, and maintained. It is usually easily recognisable by the specially-designed joints between the concrete pavers.

2.1.2 Stormwater flow is managed through temporary storage in the voids present in the underlying base courses. This flow can include runoff from adjacent areas ('run-on'). From the base courses, the stormwater is either infiltrated into the in-situ subgrade and/or captured by underdrains that trickle-feed it into further SCMs downstream.

2.1.3 Stormwater quality is managed through a combination of filtration through the gritstone and biodegradation in the underlying base courses and subgrade (if allowed).

2.1.4 PICP design needs to take into account:

i) the layout of the proposed site,

ii) the ground conditions,

iii) the proposed construction method,

iv) the local environment – in particular the proposed adjacent landscaping,

v) the anticipated hydraulic loading,

vi) the expected structural loading, and

vii) the proposed maintenance plan.

2.1.5 Several proprietary computer packages are available for the structural and hydraulic analyses including: ICPI Permeable Design Pro and CMAA Designpave.

2.1.6 Avoid using PICP at heavily trafficked intersections, in naturally dusty environments, or close to trees, as these all lead to premature failure.

2.1.7 Avoid overloading PICP with stormwater runoff from adjacent areas as this will also lead to premature failure. The 'Run-on-Factor (RoF)' – the ratio of the sum of the impermeable areas draining to the PICP to the area of the PICP – should ideally not exceed two (2).

2.2 Preliminary Design

2.2.1 Consider the pavement proposals for the envisaged development for suitable PICP locations. Optimal sites typically:

i) have low RoF,

ii) are removed from areas that might generate lots of dust or dirt,

iii) are not likely to be shaded by trees or other vegetation that might drop leaves, pollen, and/or seeds onto the pavement,

iv) are designed for slow vehicle speeds, and

v) are away from intersections or anywhere else where they are likely to be subject to considerable vehicle turning.

2.2.2 Consider the proposed development and carry out a physical inspection of the site (if possible) to identify any environmental conditions that may cause problems.

2.2.3 Identify the proposed different land-use zones in and around the site, together with their associated drainage plans, to assess the likely hydraulic loading on the PICP.

2.2.4 Produce draft PICP layout drawings.

2.2.5 Conduct a geotechnical investigation of the proposed PICP areas to determine: i) the in-situ strength of the likely subgrade, ii) the permeability of the subgrade, iii) the depth to the water table, and iv) any other factors that should be taken into account, e.g. karst conditions.

2.2.6 Modify the draft PICP layout drawings if necessary.

2.3 Structural Design

2.3.1 The structural design of PICP should comply with the latest edition of the SANRAL South African Pavement Engineering Manual (SAPEM, 2013).

2.3.2 The pavers should comply with SANS 1058:2021.

2.3.3 The paver thicknesses for pedestrian and vehicular traffic should be a minimum of 60 and 80 mm respectively.

2.3.4 Choose a paver that will give good hydraulic performance as well as providing good structural strength.

2.3.5 Select single-sized Grade 1 roadstone aggregates to SANS 1200 M:1996 Table 1 and SANS 3001-AG1:2014 for use in the bedding, the basecourse, and the subbase.

2.3.6 Geotextiles may be provided between the bedding and the basecourse (but see later) and the subbase (or the basecourse if there is no subbase) and the subgrade. The geotextile separating the PICP layers from the subgrade may be replaced by an impermeable geomembrane protected from perforation by the aggregate by a suitable high grade geotextile if no infiltration is to be allowed.

2.3.7 Ensure that all PICP installations are provided with robust edge restraints to minimize lateral movement.

2.3.8 The structural design must take into account the effect of hydraulic loading.

2.3.9 PICP should be designed for a minimum 20-year design life. With good design, construction and maintenance – including the occasional cleaning and recycling of the surface materials, PICP should have a considerably longer effective lifespan.

2.4 Hydraulic Design

2.4.1 Collect: rainfall data, candidate paver specifications, the subgrade type and associated infiltration capacity, the distance to maximum water table height, the underlying geology of the area, the proposed aggregate sizes with their associated porosity, and the specifications of the candidate geotextiles and/or geomembranes.

2.4.2 The design rainfall together with the area of the PICP and the associated run-on factor (RoF) determine the Water Quality Volume (WQV) that can be stored by the system – ignoring potential infiltration into the subgrade – before overflow occurs. The WQV can be roughly estimated by Equation 1 (Debo & Reese, 2003):

$$\mathrm{WQV} = [(0.05 + 0.009 \times I)\, A_{\mathrm{i}} + A_{\mathrm{p}}] \times d / 1000 \qquad \text{Equation 1}$$

Where: WQV = Water Quality Volume (m^3)

I = Percentage of impermeable cover (%)

A_{i} = Impermeable Area draining to the PICP (m^2)

A_{p} = Area of the PICP (m^2)

d = Critical rainfall depth (mm) – typically the 24-hour, 6-month recurrence interval storm or a specified value, e.g. 25 or 35 mm

More detailed methods are presented in ASCE/T&DI/ICPI 68-18 and the various proprietary software packages.

2.4.3 PICP is permeable because of the presence of openings between the pavers termed 'joints'. These can be created through the laying pattern, but they are more usually a consequence of specially designed vertical grooves provided along the sides of the pavers (Figure 2) that create open slots when the pavers are laid. Each paver type (Figure 3) and laying pattern responds slightly differently to hydraulic loading. Initially they all support very high infiltration rates (typically greater than 10,000 mm/hr), however they clog at different speeds. Generally, paver systems with larger void ratios – the ratio of the area of the gaps between the pavers to the total area – clog slower than those with smaller void ratios. Any paving system with an infiltration rate less than 250 mm/hr as measured by the Modified ASTM single ring infiltrometer test (Mod-ASTM – Appendix A) is generally regarded as fully clogged as the measured flow is likely to be largely seepage under the bottom of the ring rather than infiltration into the PICP.

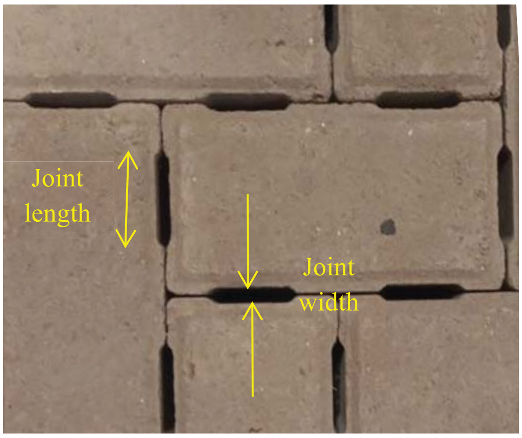


Figure 2: Joint dimensions

Figure 3: Some different PICP pavers available in South Africa

2.4.4 The joints are filled with a suitable gritstone. This should be a hard, rounded, crusher sand passing the 4.75 mm sieve but retained on the 2.36 mm sieve and washed to remove all traces of fines and dust. The selection and maintenance of this gritstone infill is essential to the operation of the PICP as it acts as a filter to trap dirt and hence prevent many pollutants from being transported any further. The use of finer infills such as sand causes premature failure of the system through clogging – often accompanied by the growth of vegetation in the joints between the pavers. Larger aggregates may be too big to fit into the joints and, in any case, will allow dirt to migrate between the pavers and into the underlying bedding layer resulting in premature failure. Similarly with the absence of a suitable gritstone. The size of the joints (Figure 3) is generally of less importance than the size of the infill material, however smaller openings will generally clog faster than larger openings while there may be restrictions on the width of the openings to, e.g. prevent high-heeled shoes from getting stuck in them or restricting the use of shopping trolleys, wheelchairs and the like. There should not be any problems if the width of the openings (between adjacent pavers) lies between 5 and 12 mm. There is no particular restriction on the length of the openings (parallel to adjacent pavers) other than the need to ensure the structural strength of the paving system which relies on 'lock-up' resulting from the friction between touching faces of adjacent pavers.

2.4.5 The pavers are laid on a 50-60 mm thick (after compacting), nominal 7.1 or 10 mm (formerly termed 6.7 and 9.5 mm respectively) single-sized bedding layer bedding layer. This provides compensation for minor differences in paver thickness and irregularities in the surface of the underlying basecourse. A geotextile may be placed under the bedding layer. Geotextiles are a convenient way of preventing bedding stone from migrating into the generally much larger basecourse aggregate. They also prevent the migration of fine material from the surface or the subgrade into the base and subbase layers, thus reducing their porosity and the threat of settlement. Certain geotextiles – typically heat-treated non-woven – promote the creation of a damp zone on their upper surface (they require a minimum water depth before they allow water to pass through – the so-called 'break-through head') that assists in the growth of micro-organisms capable of breaking down chemical pollutants. A geotextile installed under the bedding layer can also make partial reconstruction of a failed PICP easier by providing a clear break between the clogged surface and the clean base layers. On the other hand, they can become clogged (although this is uncommon), while they quickly disintegrate if subject to large shearing movements such as those caused by the movement of the overlying pavers at heavily trafficked intersections.

2.4.6 If no geotextile is placed under the bedding layer, it might be necessary to provide a 50 mm 'choke' layer (sometimes called a 'choker' layer) to prevent significant migration of the bedding aggregate into the generally much larger basecourse aggregate. This would typically be an intermediate size between the bedding and basecourse sizes determined by Equations 2-4 (US DOT, 2008).

$$d_{15\,(large)} / d_{85\,(small)} \leq 5 \qquad \text{Equation 2}$$

$$d_{50\,(large)} / d_{50\,(small)} < 25 \qquad \text{Equation 3}$$

$$d_{15\,(large)} / d_{15\,(small)} \geq 5 \qquad \text{Equation 4}$$

Where: d_x = sieve screen size at which 'x' percent of the particles, by weight are smaller.

2.4.7 The underlying base and subbase layers both distribute traffic loads as well as provide a 'reservoir' for the storage of stormwater prior to infiltration or removal by underdrain. Typical stone sizes are 20 mm (formerly termed 19 mm) for the basecourse, and 28 mm (formerly termed 26.5 mm) for the subbase. The use of single-sized aggregates with a high porosity after compaction results in considerable space for water. The porosity of a single-sized aggregate depends on particle shape, size distribution (grading), and packing efficiency and varies between 34% and 50% with a mean of 46% for nominal 20 mm stone (Alexander, 2021). Owing to the exceptionally high coefficient of permeability for single-sized stone, the surface of any water stored in the reservoir is effectively horizontal. The maximum storage capacity of the stone reservoir, termed the Reservoir Volume (RV) here, may be calculated from Equation 5:

$$RV = SV \times n \;/\; 100 \qquad \text{Equation 5}$$

Where: RV = Reservoir Volume (m^3)

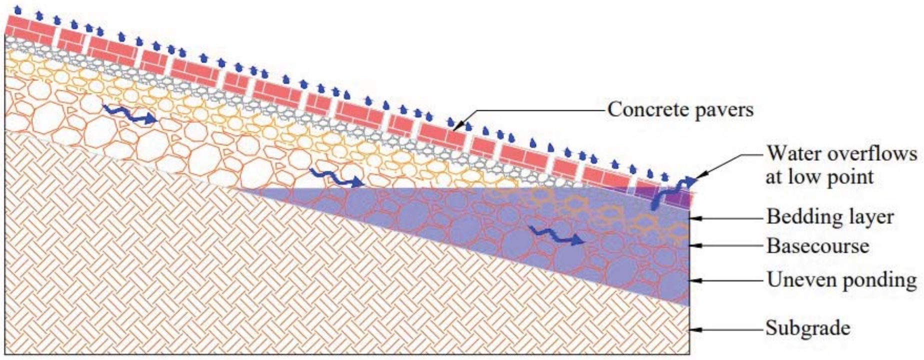
SV = Gross volume of the basecourse and subbase below the lowest part/s of the bedding layer (m^3)

n = Mean porosity of the aggregate (varies between 34% and 50%)

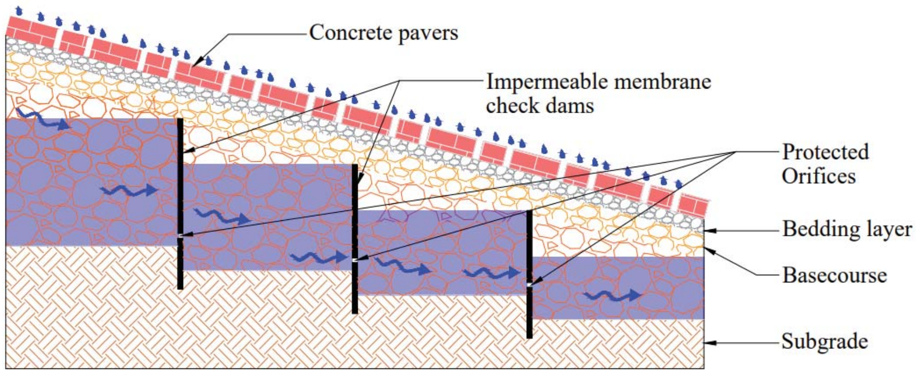
The storage capacity of the bedding is generally ignored. The fact that the stored water effectively has a horizontal surface implies that PICP is most efficient from a hydraulic point of view if laid level (no slope). Laying the PICP in a series of terraces linked by ramps is often a good way of dealing with a sloping site. However, if there are good reasons to lay PICP on a slope, the slope should be kept to less than 5% and internal water flow barriers / check dams provided to maximise the effective storage and limit the danger of stored water flowing vertically out of the PICP at low points (Figure 4).

2.4.8 It is important that fine material is excluded from the basecourse and subbase as far as possible, but given that this can be difficult to achieve, it would be prudent to select a design porosity on the lower side, e.g. 40%. The required RV depends on the rainfall / runoff characteristics, infiltration into the subgrade (if allowed), and outflow via the underdrains (if any provided) but ultimately should at least accommodate the Water Quality Volume (WQV) needed to deal with water quality, i.e. a conservative estimate is $RV \geq WQV$. More detailed advice is provided in ASCE/T&DI/ICPI 68-18; proprietary computer packages can assist with more advanced design. The overall thickness of the basecourse and subbase layers are the greater of the structural and hydraulic requirements.

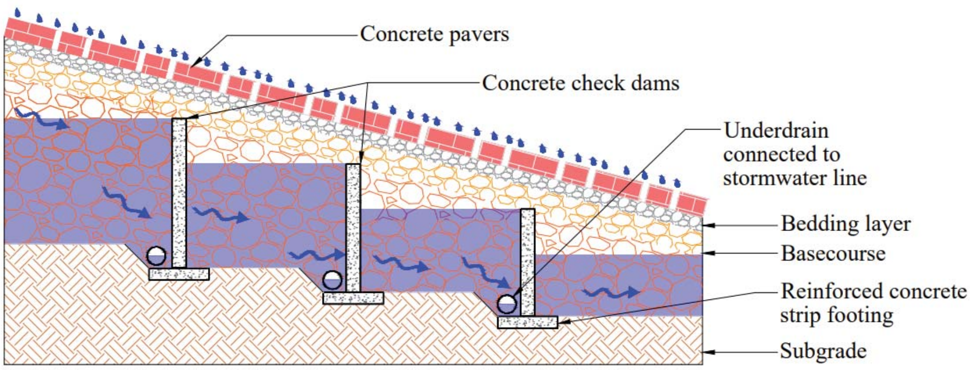
2.4.9 The maximum height of the water table and the subgrade type – and associated infiltration rate – determines whether it is reasonable to assume full infiltration of the stormwater into the subgrade – or whether drainage will require a subsurface drain either in part or full (Figure 5). In certain situations, most notably in karst regions, infiltration should be prevented to lower the risk of slippages or sinkholes.



(a) Bad practice – reduced WQV, water flows out of PICP at low point

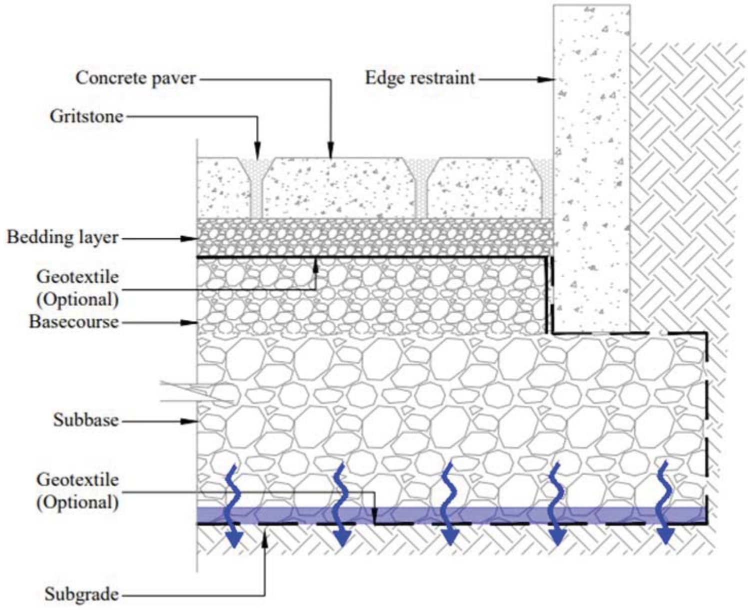


(b) Good practice 1 – internal check dams linked by protected orifices

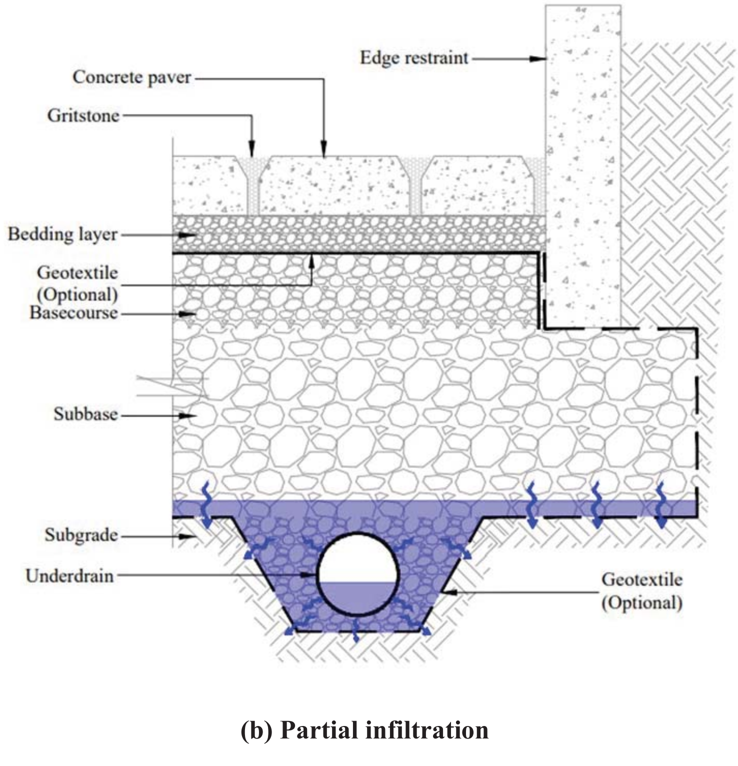


(c) Good practice 2 – internal check dams emptied by underdrains

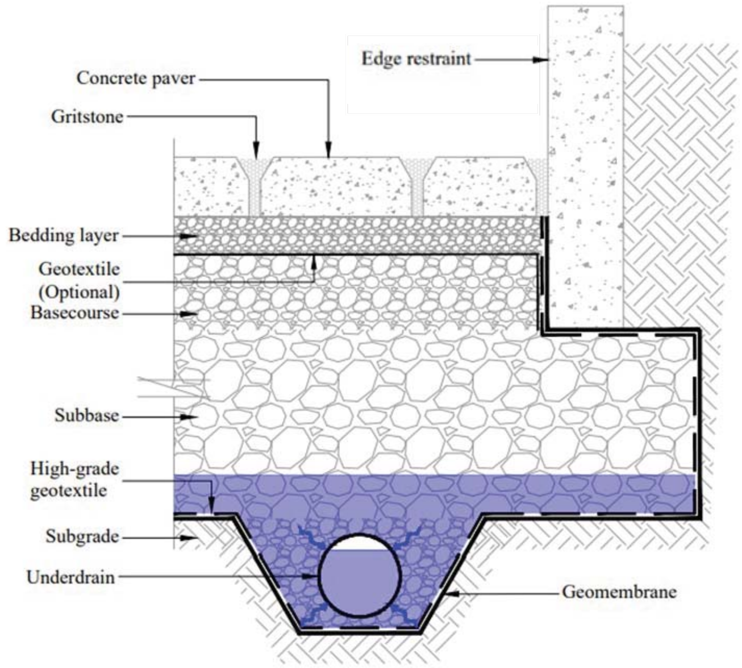
Figure 4: PICP layouts on sloping ground



(a) Full infiltration



(b) Partial infiltration



(c) No infiltration

Figure 5: PICP configurations

2.4.10 A geotextile or geomembrane is usually placed between the base / subbase and the subgrade to prevent intermixing – and the movement of water in the case of an impermeable membrane – between the two. This includes up the sides to prevent lateral intermixing. They would be specified with the help of an expert.

2.4.11 Particular care must be taken with the protection of services that run through the PICP layers including any underdrains. Any geotextile or geomembranes penetrated by these services also require special attention.

2.5 Additional design considerations

2.5.1 Use a no-infiltration PICP configuration where the water table is likely to come within 600 mm of the subbase.

2.5.2 Leaves and pollen falling from trees and shrubs quickly clog PICP. If the overall design includes vegetation overhanging the PICP, then indigenous evergreen varieties with minimal pollen drop are preferred.

2.5.3 Consider sediment traps – which can be as simple as grass strips – wherever there is any chance of material being washed onto the PICP from adjacent areas. Particular attention should be given to planters or adjacent slopes that might generate sediment that could find its way onto the PICP.

2.5.4 Keep the PICP at least three metres away from building structures. Ideally ensure that the runoff from these structures is directed away from the PICP and an impermeable membrane encases the PICP in the vicinity of the structures to prevent the concentration of infiltrated rainwater around the foundations. If the runoff from the building is designed to be absorbed into the PICP, then ensure that adequate erosion protection is placed at the bottom of any downpipes and provide sediment traps around all outlets. Consider passing the runoff through a filter prior to introducing it into the PICP layer-works.

2.5.5 PICP should not be installed at intersections or any other area where considerable braking and turning may be expected as this tends to open up the gaps between the pavers and damage any underlying geotextiles leading to premature failure.

2.5.6 Limit the RoF as the larger the area serviced by the PICP, the faster it will clog. Savings in PICP construction may well be off-set by increases in maintenance costs. In general, a RoF of 2 should not be exceeded; a RoF of 0 (the paver only handles direct rainfall) is best from a maintenance / longevity point of view (Figure 6).

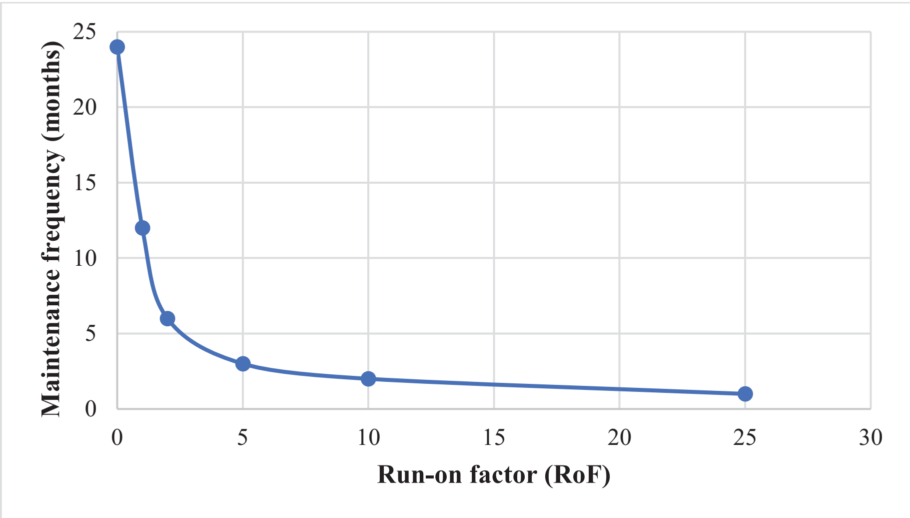


Figure 6: Typical maintenance frequency versus RoF curve (After Winston, 2019)

2.5.7 Carry out a Life-Cycle Cost analysis for the project and adjust the design as necessary.

2.5.8 Draw up a detailed Maintenance Plan appropriate to the site.

3. PICP Construction

3.1 Workflow plan

3.1.1 The Design Engineer should hold a pre-meeting of all the involved stakeholders before the construction of the pavement to discuss the construction sequence.

3.1.2 The Contractor must prepare a detailed workflow plan ahead of commencement of work that should include:

i) the routing of access roads – which should preferably avoid future PICP areas.

ii) the proposed stormwater management plan (SMP) showing how stormwater will be deviated away from the future PICP areas during construction.

iii) the sources of all PICP materials and how they will be stockpiled on site prior to use in such a manner that they will not be contaminated with dust and site debris.

iv) how the PICP layers will be protected from premature clogging as they are constructed. Typical sources of sediment include adjacent landscaping and the movement of traffic over the PICP. The PICP should preferably be constructed last – and ideally during the dry season. If it is necessary to use the PICP as an access for construction, then it must be protected by an impermeable membrane that can be removed at the end of the construction to expose the PICP. A temporary road surface can then be laid upon this.

3.1.3 The Workflow plan must be approved by The Engineer before work can commence.

3.2 During construction

3.2.1 The construction shall be carried out in strict accordance with SANS 1200 MJ (Segmented Paving) with the exception of the clauses referring to sand. With the exception of the gritstone, sand should be excluded from PICP.

3.2.2 All aggregates should be single-sized from approved sources. They should be stored, as far as is reasonable, in a dust-free environment. Cover if necessary.

3.2.3 Any geosynthetics and drainage pipes must be handled and stored with care – free from water and any possibility of being damaged.

3.2.4 The aggregates should be washed before use to reduce the risk of premature clogging. Hose down the aggregates while they are stacked taking care to ensure that wash-off is contained on site and safely disposed in accordance with the requirements of the National Environmental Management Act (NEMA) No. 107, 1998. It may be necessary to move the aggregate around during the washing process to expose underlying layers. After drying, the aggregates must be free of material passing the 0.075 mm sieve.

3.2.5 Avoid excessive compaction of the subgrade if full or partial infiltration PICP configurations are to be installed. Light scarification of the surface prior to construction may be prescribed by The Engineer.

3.2.6 If geosynthetics are used, the overlap between adjacent sheets should be at least 200 mm unless otherwise stated by the manufacturer or The Engineer.

3.2.7 Each stone layer should be compacted by a vibrator in layers of no more than 150 mm until they are locked up in accordance with SANS 1200 MJ whereupon there should be no visible movement.

3.2.8 Exposed PICP layers should be covered in-between construction activities to reduce the risk of being contaminated by dirt.

3.2.9 Vehicles should ideally not be allowed to drive on the PICP or any of its constituent layers during construction on the site. If this is unavoidable, then provide a sacrificial 100 mm aggregate layer on top of a sacrificial geotextile to protect the underlying PICP layers. Once the construction is complete – or the contractor is ready to place the next layer – the sacrificial geotextile and aggregate layer can be removed.

3.2.10 Once the pavers have been installed within their edge restraints, the gritstone needs to be brushed into the openings until they are full. Light vibration with a plate compactor will help ensure that the gritstone fills the entire joint volume down to the bedding layer. Several rounds of gritstone addition – with vibration – may be required until all the joints are completely filled. Any loose gritstone should then be swept away from the surface.

3.2.11 Once the PICP is complete, it should be tested. It should be impossible to keep water on the surface irrespective of the rate at which it is applied (newly laid PICP typically supports an infiltration rate of greater than 10,000 mm/hr). If there is any sign of ponding, the associated section needs to be opened and reconstructed. Similarly if there is any sign of clogged openings.

3.2.12 Throughout the construction, adjacent areas should be monitored to ensure that they do not impact the PICP. Particular attention should be paid to sources of dust, leaves, pollen, etc.

3.2.13 Once construction of the PICP is complete, details of the installation (see Appendix C for a template that could be used for this) plus copies of the approved Maintenance Plan should be handed over to the Owner of the installation (or their approved agent) and the Local Authority by The Engineer.

3.3 During the Defects Liability Period

3.3.1 Regularly check for – and eliminate – any significant sources of dirt coming onto the PICP.

3.3.2 It will be necessary to add more gritstone to the PICP surface after it has been in use for a month or two. Inspect and potentially add more gritstone at least every three months during the Defects Liability Period.

3.3.3 The PICP must be tested before the Defects Liability Period is up. The structural integrity may be determined by examining the surface for any sign of horizontal creep, grit pumping, rutting, broken and/or missing pavers, excessive joint width, and damaged edge restraints. The hydraulic capacity should be tested in the manner described in Section 3.2.11 – with the same consequences if it fails.

4. PICP Maintenance

4.1 Introduction

4.1.1 Every PICP installation should have an approved Maintenance Plan that should be strictly adhered to.

4.1.2 PICP maintenance may be classified as 'routine', 'restorative', or 'reconstruction'.

4.1.3 There are two components to PICP maintenance: structural and hydraulic. The former ensures that the pavement structure is sufficient to carry traffic while the latter ensures the hydraulic performance requirements are met.

4.1.4 Appendix F provides a template for a maintenance inspection report.

4.2 Routine maintenance

4.2.1 Most of the flexible pavement maintenance requirements apply to PICP with the obvious exception of asphalt resurfacing.

4.2.2 The surface should be inspected at least annually for: horizontal creep, grit pumping, rutting, broken and/or missing pavers, excessive joint width, and damaged edge restraints – and the appropriate remedial action taken.

4.2.3 The biggest threat to the functioning of PICP as a SCM is clogging. To understand more about this phenomenon, refer to the accompanying report on Clogging in Permeable Interlocking Concrete Pavements (PICP).

4.2.4 The PICP should be regularly inspected for signs of clogging. The ideal frequency of the inspections is site specific and always highly dependent on the RoF (Figure 6) – the higher the RoF, the more frequent the maintenance requirement. The PICP should be inspected at least every three months during the first year of operation; after that an annual inspection should be adequate for a well-designed PICP. This annual inspection should preferably be conducted shortly before the commencement of the rainy season, e.g. February/March for Cape Town and August/September for Johannesburg. If the RoF is increased due to development, the inspection frequency must be re-assessed with guidance from the original designer if possible.

4.2.5 There are four types of clogging: Type I (in the top 10-25 mm of the openings between the pavers), Type II (on the top of the bedding layer immediately underneath the openings between the pavers), Type III (clogging of the bedding layer and the underlying geotextile), and Type IV (clogging through the full depth of the system, i.e. total failure) (Figure 7). Type I is both the most common and the easiest to address. A good maintenance plan will seek to both slow down the clogging rate and restrict it – as far as possible – to Type I.

(a) Type I clogging

(b) Type II clogging

(c)Type III clogging

(d) Type IV clogging

Figure 7: Different types of clogging

4.2.6 Check for the following:

i) The state of the pavers (see 4.2.2).

ii) Whether the openings between the pavers are free of dirt and/or vegetation and filled with clean gritstone.

iii) Sediment caught in any traps or underdrains that requires removal.

iv) Any potential sources of fine material that might clog the PICP including exposed soil, overhanging branches, unregulated discharges, etc.

4.2.7 Carry out rapid infiltration tests, e.g. the Modified SWIFT Test (Mod-SWIFT – Appendix B) on a representative sample of the PICP to identify areas of concern where the infiltration rate has dropped to less than a nominal 1000 mm/hr. Follow up with Mod-ASTM tests (Appendix A) in critical areas for more 'accurate' data. Infiltration rates of less than a nominal 250 mm/hr can be considered to be clogged (since it is almost impossible to stop leakage around the base of the test apparatus, anything less than 250 mm/hr is likely to be leakage rather than infiltration). Infiltration rates 250-1000 mm/hr indicate partial clogging that needs some sort of restorative maintenance (Section 4.3). Any sign of ponding after rainfall indicates a fully clogged PICP. See Appendix D for a template for the infiltration testing.

4.2.8 Repair any structurally defective PICP sections (see Section 4.2.2).

4.2.9 Trim overhanging vegetation. Replant vegetation on adjacent bare slopes to reduce the sediment threat.

4.2.10 Clean out observation wells, underdrains, and sediment traps.

4.2.11 The rate at which sediment is trapped in the PICP may be slowed down by regularly sweeping the surface. Note, however, that sweeping the surface without the prompt removal of loose material can increase the rate of clogging. Furthermore, brushes can push dirt and debris deeper into the PICP openings exacerbating the clogging. Alternatively, pass a suitably designed vacuum truck (called a 'Regenerative Sweeper' in the US) over the surface to loosen and remove loose dirt and debris.

4.2.12 Ensure that the openings between the pavers are filled with gritstone before reopening the PICP to traffic.

4.2.13 Document all the maintenance that has been performed. Photographs are particularly helpful in this regard. Check against the Maintenance Plan for issues that might need attention. See Appendix F for a template for a PICP inspection report.

4.3 Restorative maintenance

4.3.1 Inspections potentially coupled with diagnostic assessments may prompt the need for restorative maintenance where a major intervention is needed to substantially improve the infiltration capacity of the PICP. See Appendix E for instructions on diagnostic assessments.

4.3.2 In the case of **Type I clogging** – in the top 10-25 mm of the joints – it is usually possible to blow out the majority of the sediment using a compressed air blower with an 8-10 mm internal diameter nozzle. It is usually relatively easy to blow out the top 25 mm of material; 50 mm can be blown out with some effort. The sediment – likely mixed with gritstone – should be immediately removed with a dustpan and brush or a vacuum cleaner taking care not to allow it to fall back into the joints. This type of maintenance will not restore the PICP to new condition, but should realise a 50% improvement.

4.3.3 If it is not possible to restore the infiltration capacity of the PICP to at least 1000 mm/hr as measured by the Mod-ASTM test (Appendix A), then the pavers should be lifted in selected problem areas to see where the clogging has taken place (see Appendix E for guidance on how this might be done). Often, **Type II clogging** is the problem. This type of clogging is usually easy to identify because when the pavers are lifted the deposits that have travelled all the way down through the joints will outline their previous positions. Infiltration tests performed on the bedding adjacent to the deposits will generally show a high infiltration capacity. If this is the case, then it will be necessary to remove, wash – taking care to observe the requirements of NEMA – and replace the bedding. This will be made easier if a geotextile was used under the bedding layer as it should be possible to remove the bedding layer together with the underlying geotextile without disturbing the basecourse which should still be clean. The washed bedding material will then be placed on top of a new geotextile and the pavers re-laid and re-gritted. The basecourse infiltration capacity should be tested before the geotextile is replaced. If it has a low infiltration capacity, this implies a Type IV clogging failure.

4.3.4 In some cases, so much fine material has entered the bedding layer that both the bedding layer and the underlying geotextile are clogged (infiltration rate less than 250 mm/hr) in a **Type III clogging** failure. In this case – as with Type II – it should be possible to remove and replace the bedding material on top of a new geotextile. The basecourse infiltration capacity should be tested before the geotextile is replaced. If this also has a low infiltration capacity, this implies a Type IV clogging failure. Note that in the case of a Type III failure there is likely an associated design flaw – such as proximity to high vehicle turning movements or sources of fine material – that should be addressed prior to rehabilitation.

4.3.5 In the case of a **Type IV clogging** failure, fine material has worked its way through all the layers and the only solution is to reconstruct the PICP from scratch (‘reconstruction’). A Type IV failure is likely the consequence of poor design and/or construction, for example poor quality control associated with the aggregates whereby fine material is either not washed out prior to laying, or allowed to get into the system before capping.

4.3.6 If the PICP gets badly impacted by toxic spills, the pavers should be lifted and the affected aggregate layers and geotextile (if present) removed and replaced. Note that oil drips from vehicles are mainly an aesthetic problem. They are usually trapped in the surface layers and degrade with time. They do, however, release hydrocarbons that can find their way into the groundwater and/or underdrain discharge.

4.3.7 Ensure that the openings between the pavers are filled with gritstone that has been lightly compacted before reopening the PICP to traffic.

4.3.8 Ensure that any material that is removed from site is safely disposed of in accordance with NEMA.

4.3.9 PICP maintenance must always be documented for future reference.

4.3.10 Eventually there will come a time when maintenance has negligible impact on a failed PICP. At this point, the only available remedy is reconstruction. If carefully done, it should be possible to salvage, clean and re-use most of the PICP aggregates and pavers although all geotextiles must be replaced.

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Appendix A: Modified ASTM single ring infiltrometer (Mod-ASTM)

A1 Generally regarded as the standard test method for PICP (modified from ASTM C1781).

A2 The test apparatus consists of an approximately 500 mm high, 315 mm outside diameter unplasticized vinyl chloride (uPVC) Class 6 pipe (300 mm inside diameter) that has a 10 mm neoprene strip glued to the lower end to provide a seal against the PICP (Figure A-1). The inside of the pipe is marked with two lines 10 mm and 15 mm respectively above the neoprene strips. A metal rod is inserted through two holes drilled near the top of the pipe and weights hung from it to help load the pipe and thus reduce the leakage under the neoprene strips.

A3 Place the apparatus on the test spot. Small neoprene pieces may also be inserted into the joints between the pavers for the same purpose (Figure A-2).

A4 If the surface of the PICP is not already wet, the inside of the apparatus may need to be pre-wetted with 3.6 litres (= 3.6 kg) of water.

A5 The water is steadily poured from a bucket into the ASTM apparatus while trying to maintain a 10 to 15 mm water head over the PICP for as long as possible. The time taken (T to the nearest second) for 18 litres (= 18 kg) of water to infiltrate through the PICP is measured.

(a) Upright (b) Underside

Figure A-1: Mod-ASTM apparatus

A6 If the test time is longer than 15 minutes, the PICP can be considered partly or fully clogged and the test stopped. The quantity of water remaining in the bucket is then determined by weighing the bucket with and without the water in it. This is then deducted from the initial 18 litres to give the approximate quantity of water used in the test (M in litres). Note that much of the flow rate measured under these circumstances will be leakage under the apparatus rather than through the PICP surface (Figure A-3).

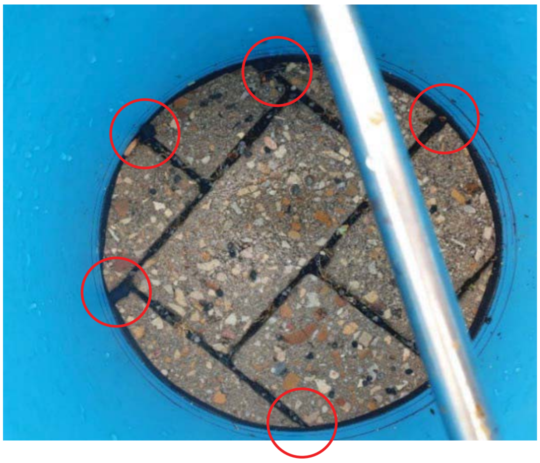

Figure A-2: Neoprene pieces plugging the joints in Mod-ASTM

Figure A-3: Mod-ASTM leakage

A7 Use Equation 6 to estimate the PICP infiltration capacity (nearest 100 mm/hr).

$$I = 51{,}000\ M / T \qquad \text{Equation 6}$$

Where: I = Infiltration rate (mm/hr)
M = Mass of infiltrated water (kg)
T = Time (s)

A8 If $250 < I < 1000$ mm/hr, the PICP is partially clogged; if $I \leq 250$ mm/hr then it can be considered completely clogged (it is likely that the flow is largely leakage).

Appendix B: Modified SWIFT (Mod-SWIFT)

B1 Used to give a rapid indication of the state of the PICP.

B2 Modified from the Stormwater Infiltration Field Test (SWIFT) (Lucke *et al*., 2015).

B3 The test apparatus consists of a bucket resting on 60 mm high legs (Figure B-1). The bottom of the bucket has a 40 mm hole drilled through its centre that is temporarily sealed with a bathroom plug to prevent water from escaping the bucket prior to the test. A string is tied to the plug to allow it to be rapidly removed.

(a) Inside of bucket **(b) Legs**

Figure B-1: Mod-SWIFT apparatus

B4 The bucket is placed on the spot to be tested. The surface must be dry.

B5 The bucket is filled with six litres of water. It is helpful to have the height attained by the six litres of water pre-marked on the inside to obviate the need to measure the water separately for each test.

B6 Once the water is at rest in the bucket, rapidly pull the plug with the string to allow the water to flow out of the bottom of the bucket.

B7 Immediately remove the bucket once it is empty – remembering to replace the plug for the next test.

B8 Measure the longest wetted length, *a*, to the nearest 0.1 m with a tape measure. Then measure the greatest extent of the wet patch, *b*, perpendicular to *a*, to the nearest 0.1 m (Figure B-2).

B9 Use Equation 7 to estimate the Mod-SWIFT infiltration capacity of the test spot (to the nearest 100 mm/hr). Anything less than 1000 mm/hr can be considered as clogged. Check using the Mod-ASTM (Appendix A). Both methods are increasingly inaccurate as the infiltration rate decreases.

$$I = -930 \ln(a \times b) + 2200 \quad \text{Equation 7}$$

Where:
- I = Infiltration rate (mm/hr)
- a = longest wetted length (m)
- b = widest wetted perpendicular to a (m)

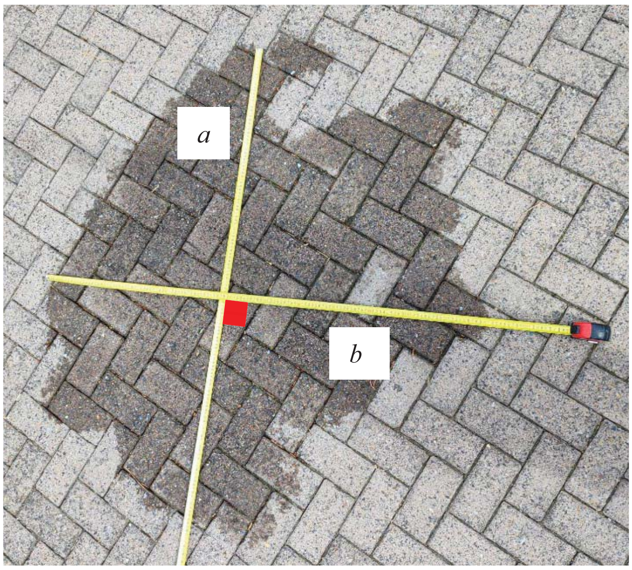

Figure B-2: Mod-SWIFT measurements

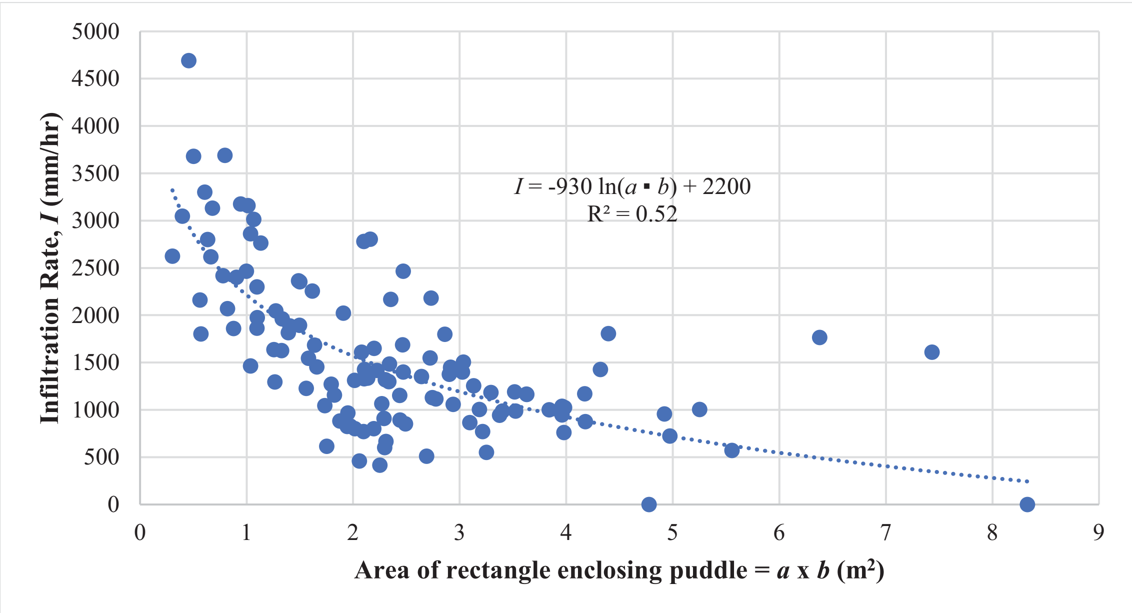

Figure B-3: Mod-SWIFT to Mod-ASTM conversion

Appendix C: Template for Details of PICP installation

Name of development				
Street address				
Town / City				
Province				
Google Map pin				
Property manager			**Contact details**	
Consultant				
Contractor				
Year of construction				
Maintenance	**Contractor**		**Contact Details**	
	Recurrence			
	Method			
PICP area	**Permeable area**			
	Run-on factor			
	Google Earth plan			
Traffic characteristics				
Pavers	**Type**			
	Depth			
	Joint width			
	Paver dimensions			
	Paver opening ratio			
	Photos			
Geofabric	**Type**			
	Location			
	Function			
	If none; choke layer?			
Layerworks	**Gritstone**		**Thickness (mm)**	
	Bedding			
	Base course			
	Subbase			
Subgrade				

Appendix D: Template for PICP testing

General

D1 Locate site.

D2 Request access to the site to perform the infiltration tests.

D3 Take photos of any features that may be important in understanding the performance of the PICP site such as vegetation around the site, loose sediment, spacing between the pavers filled with dirt, broken pavers, rutting, etc,

D4 Choose the test spots for the infiltration tests and mark these up on a Google Earth clip to help give the physical context.

D5 Label the test spots using the following code: [PICP site code]-[PICP section]-[Test spot]-[Test year]. For example, Test spot A carried out in Section 1 of the Grand Parade in 2021 might be reported as GRP-1-A-2021.

D6 Barricade the working space around the designated test spots providing traffic control if necessary. Ensure all personnel are wearing appropriate PPE. Keep the public at a safe distance.

D7 Determine and record the infiltration capacity of the PICP at the identified test spots using either Mod-ASTM (standard) or Mod-SWIFT as appropriate using the following template or similar.

Location:

Provide maps showing the location of the site and position of the test spots

Date of test:

Carried out by: Contact No.:

Surface infiltration rates for each test spot

Test spot ID	Condition and comments	Test Type	Mod-ASTM		Mod-SWIFT		
			Time (s)	Infiltration rate (mm/hr)	*a* (m)	*b* (m)	Infiltration rate (mm/hr)
		Pre-maintenance:					
		Post-maintenance:					
		After re-gritting:					
Add blocks as necessary		Pre-maintenance:					
		Post-maintenance:					
		After re-gritting:					

Appendix E: Instructions for diagnostic assessments

E1 Carry out baseline Mod-ASTM (Appendix A) infiltration tests to locate areas of concern – typically areas with infiltration rates less than 1000 mm/hr.

E2 Select one or more of the areas of concern and isolate areas no smaller than 3 m x 3 m with suitable barriers to protect the public from flying debris.

E3 Attempt to blow out the dirt from the joints using a high-velocity air blower through a suitably-sized nozzle. Ensure that the ejected dirt is carefully removed, e.g. with dustpan and brush, so as not to fall back into the joints.

E4 Carry out Mod-ASTM infiltration tests on the selected test spots. If there is a substantial improvement to greater than 1000 mm/hr, then the PICP was likely exhibiting Type I clogging (in the top 25 mm of the joints – Figure E-1).

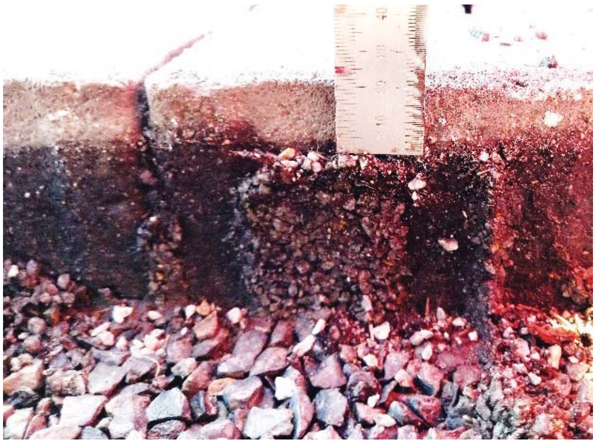

Figure E-1: Type I clogging (in the joints)

E5 If dissatisfied with the improvement in the infiltration rate, e.g. infiltration rate still less than 1000 mm/hr, carefully lift the pavers for further investigation. It is likely that there will be ‘wedges’ of dirt below the joints (Figure E-2). If this is the case, it is indicative of Type II clogging (on the top of the bedding layer immediately underneath the joints).

E6 Record and take pictures of the state of the bedding. at each test spot, perform a Mod-ASTM infiltration test on the bedding. There are usually only two clear results from this test owing to the stony nature of the bedding *viz*. not clogged or completely clogged. The latter will usually be accompanied by high proportions of fines mixed in with the bedding aggregate clearly indicating Type III clogging (clogging of the bedding layer and the underlying geotextile – Figure E-3).

Figure E-2: Type II clogging (below the joints)

Figure E-3: Type III clogging (of the bedding)

E7 If the bedding layer does not appear completely clogged (remember that water can usually easily flow laterally which must be taken into account in this assessment) and a geotextile was provided under the bedding, gently remove the bedding to access the geotextile taking care not to damage it.

E8 Record and take pictures of the state of the geotextile. Perform a Mod-ASTM infiltration test on the geotextile. If the geotextile is clogged, this likely means Type III clogging (clogging of the bedding layer and the underlying geotextile) (Figure E-3). If not, then the clogging is likely Type II (on the top of the bedding layer immediately underneath the openings between the pavers – Figure E-2). Alternatively, the geotextile may be damaged to the point where it serves no function (or is absent) (Figure E-4).

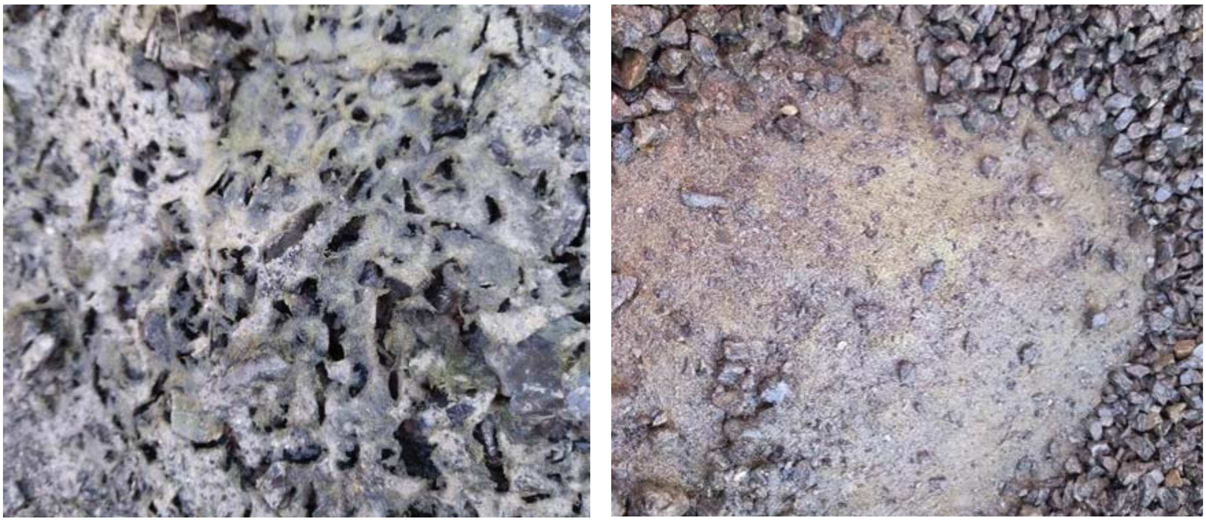

Figure E-4: Top geotextile failure

E9 If the geotextile appears clogged, carefully cut out a section so that the state of the underlying base course can be assessed (Figure E-5). Perform a Mod-ASTM infiltration test if there is concern that it may be clogged. If the base course is unclogged, then the clogging must be Type III (clogging of the bedding layer and the underlying geotextile). If the base course is clogged, then the clogging is Type IV (in the base courses) which should prompt a review of the design and construction methods as this type of failure is rare (Figure E-6).

Figure E-5: Type IV clogging (in the base courses)

E10 If the base course is clogged, carefully excavate a hole down through the layers down as far as the lower geotextile – if present – to see its condition (Figure E-6). Pay attention to the particle size distribution of each layer – each layer should be single-sized. If the layers have mixed particle sizes it is likely that there was a construction error, i.e. the contractor didn't use single-sized aggregate.

Figure E-6: Damaged bottom geotextile

E11 Once the investigation has been completed, carefully reconstruct the aggregate layers ensuring that they are well compacted. Replace the pavers and fill the joints with washed gritstone (Figure E-7).

Figure E-7: Repaired PICP test spot

E12 Record all results.

Appendix F: Template for PICP inspection report

(adjust as appropriate)

Inspector's name		**Contact No.**	
Date of inspection		**Date of last inspection**	
Name of development			
Street address			
Town / City			
Province			
Google Map pin			
Property manager			
Consultant			
Contractor			
Year of construction			
Structural	**Horizontal creep?**		
	Grit pumping?		
	Rutting?		
	Broken / missing pavers?		
	Excessive joint widths?		
	Damaged / displaced edge restraints?		
Hydraulic	**Changes to stormwater design (including RoF)?**		
	Ponding?		
	Visually clogged joints?		
	Sediment / debris etc coming onto the surface?		
	Test results?		
	Diagnostic assessments?		
Other observations			
Action taken			

Inspector:........................ Signature:................... Place:................... Date:................

Original to be kept in the offices of the Property Owner, copy to be made available to the local authority on request.