PAPER 2

THE NEW SA PERMEABLE INTERLOCKING CONCRETE PAVEMENT (PICP) GUIDELINES

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ABSTRACT

Urbanisation has resulted in much land becoming impervious owing to the construction of roads, parking lots, driveways, and buildings. Permeable Interlocking Concrete Pavements (PICP) promote the infiltration of stormwater runoff through the wearing course with temporary storage and some treatment in the underlying aggregate layers. Unfortunately, inspections carried out since 2017 by Universities of Cape Town (UCT) and the Witwatersrand (Wits) at numerous sites in Cape Town, Ekurhuleni, Johannesburg and Pietermaritzburg have shown that many have failed.

The Water Research Commission of South Africa (WRC) thus funded a two-year study, 2021-2023 (C2021/2022-00436), by UCT and Wits to carry out research leading to the development of South African PICP guidelines that has recently been published in two volumes: '*Guidelines for Permeable Interlocking Concrete Pavements (PICP) in South Africa (TT 913) – Volume 1: Clogging in Permeable Interlocking Pavement (PICP)*', and '*Volume 2: Guidelines for the Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement (PICP) in South Africa*'.

The research showed that on many sites there was clear evidence of poor design, poor construction and/or lack of adequate maintenance. Considerable effort was put into understanding the clogging phenomenon and methods to slow down and potentially reverse this threat. Aspects that received attention included the impacts on clogging of: age of pavement; Run-on-Factor (RoF – the ratio of the impermeable area that drains to the PICP to the PICP area itself); paver type; the upper geotextile; various environmental factors such as proximity to unstable slopes, overhanging trees, planters, or sources of wind-blown sand; paver type and installation; the selection of the gritstone between the pavers; the possible impact of the upper geotextile on clogging; and the efficacy of different maintenance techniques. All insights were incorporated in the guidelines.

INTRODUCTION

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 (SA) 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 (CSIR, 2019).

In many countries, including SA, a more sustainable approach to 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 from roads and parking areas by promoting the infiltration of the stormwater through the wearing course into the underlying layers which are specially designed to store water prior to infiltration and/or downstream discharge – thereby overturning the conventional road design approach which sees the wearing course as a waterproof surface to protect the pavement layers from water. PPS can be adapted to make effective stormwater harvesting and storage devices 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. Overall, this will increase the resilience of the systems to the impacts of development.

Permeable Interlocking Concrete Pavements (PICP) are the most widely used PPS both internationally and in SA – with the first example in SA being constructed in 2008. PICP consists of specially designed concrete block pavers placed on the single-sized stone base layers. Specially designed grooves create gaps between the pavers, termed 'joints', that allow surface water to pass through the surface. Specially selected coarse sand in the 2-5 mm range, termed 'gritstone', is placed between the paving blocks to hold back sediment (ASCE, 2018). Geotextiles may be placed between the bedding layer and the top-most base layer, and between the bottom and sides of the lowest base layer and the in-situ material, to separate the layers, improve the runoff water quality, and prevent migration of underlying soil material into the pavement structure. Stormwater is temporarily stored in the base layers where it may undergo some improvement in water quality as a consequence of sedimentation and bacteriological activity (Sehgal et al., 2018). Ultimately, the stormwater infiltrates into the subgrade and/or is removed by sub-surface drains (Woods Ballard et al., 2015; ASCE, 2018).

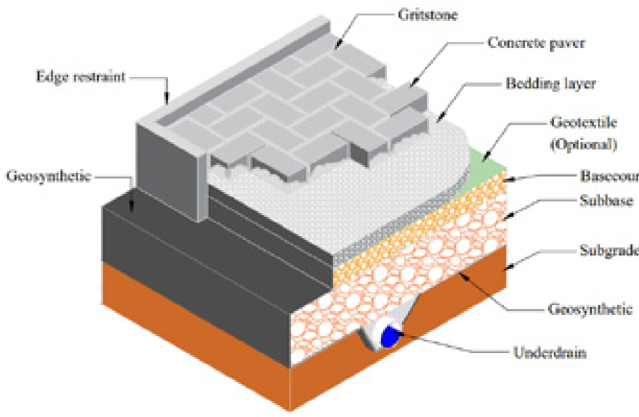

FIGURE 1: *Typical PICP section (After ICPI, 2020)*

Unfortunately, despite increasing experience in PICP construction in SA 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 all of them were either clogged or nearly clogged i.e., the so-called permeable paving had ceased to be permeable. In some places, the pavers had been dislodged. On many sites, there was clear evidence of poor design, poor construction and/or lack of maintenance. Factors that appeared to be contributing to PICP failure included:

- Loose fine soils from surrounding areas transported by wind or runoff onto the PICP surfaces.
- High run-on of sediment-laden stormwater onto the PICP from adjacent impermeable surfaces.
- Poor construction practices leading to premature failure such as the use of inappropriate filling material such as sand, dirty aggregates, or the lack of suitable edge restraints.
- Little or no maintenance that might have slowed the inevitable clogging of the PICP. In many instances, there was little evidence of the gritstone between the pavers thus allowing the accumulation of fine sediment material in the lower parts of the openings between the pavers.
- Rutting or differential settlement of the PICP structure owing to the settling of the underlying base layers.
- Unsuitable environmental conditions such as proximity to vegetation with high leaf or pollen drops or unacceptable sediment exposure.

Clogging usually comes about as a consequence of the build-up of fine material between the joints of the pavers and within the pavement sublayers. Severe clogging inhibits runoff surface infiltration (Støvring et al., 2018). While the source of this fine material is usually from local environmental conditions, laboratory tests have shown that considerable quantities are also introduced through the use of unwashed aggregates (Biggs, 2016). Concerns have also been raised about the potential blockage of any geofabric placed between the bedding and base-course layers due to the migration of fine material from the bedding aggregate or surface. Typical practice in the UK is to install geotextiles to improve the quality of runoff (Charlesworth et al., 2017). Further, geotextile protects the underlying pavement layers from possible migration of fine material from the surface (DPLG, 2010). However, various USA guidelines and ASCE/T&DI/ICPI 68-19 (ASCE, 2018 – the US standard for Permeable Interlocking Concrete Pavement) warn that it may increase the risk of premature PICP clogging through the trapping of fine material on its surface (Hein & Smith, 2015).

The SA construction industry currently adapts various international guidelines and standards for the design, construction and maintenance of PICP. This has resulted in inconsistent PICP practices across the country as different designers have taken different approaches. It appears highly likely that PICP is failing because of the lack of understanding by local designers of the chief mechanisms involved in PICP clogging and how these can be mitigated.

In 2021, the Water Research Commission of South Africa (WRC) awarded a two-year contract (Project No. C2021/2022-00436) to researchers at the Universities of Cape Town and the Witwatersrand to:

1. Identify the most appropriate PICP designs for SA conditions.
2. Identify effective maintenance equipment and methods.
3. Develop 'User-friendly' guidelines for the design, construction and maintenance of PICP in SA.

METHOD

The study had four main components:

1. Literature review of the design, construction, and maintenance of PICP through the consideration of journals, case studies, conference papers, books, websites, student dissertations, seminars, standards and guidelines.
2. Collection of data from existing PICP installations in Cape Town and Gauteng.
3. Laboratory investigations into the role of geotextiles and pavers in possible PICP clogging.
4. Input from a specially created PICP Working Group comprising experts from academia (inclusive of the USA and UK), local authorities, consultants, and suppliers.

PICP site selection criteria

It was thought that the best way to understand how PICP is performing in SA would be to inspect and test a range of installations in the field. A list of PICP sites was compiled with the assistance of local authority representatives, paving suppliers, and consultants. Most of the sites were situated in and around Cape Town and Johannesburg. Representative sites were then selected for possible investigation considering their: geographical location, pavement design, environmental factors such as vegetation and sediment proximity, site slopes, run-on factors, traffic loading, method of construction, known state of clogging, age, and known maintenance. Permission to perform infiltration and pavement investigative tests on these sites was then requested. Overall, eleven test sites were examined: nine in Cape Town, a coastal, winter rainfall situation, and two in Gauteng, an inland, summer rainfall situation (Table 1).

The selection of potential test spots at each site was guided by the characteristics of the PICP sections. Typical considerations included: the proximity of vegetation and debris sources, traffic loading, and probable clogging state as determined by visual inspection. The number and location of the test spots was largely governed by the size of the site. Surface infiltration tests were then performed using the Modified ASTM single-ring infiltrometer (Mod-ASTM) and/or the Modified Stormwater Infiltration Field Test (Mod-SWIFT). The infiltration results were compared with previous data when available to give an indication as to how the PICP performance was deteriorating over time. Maintenance trials and diagnostic assessments were carried out at selected sites.

TABLE 1: *Existing PICP installations used for the field investigations (all parking areas and associated access roads; see Motlatsi & Armitage, 2023 for further details)*

Location	Infiltration test sites	Age at time of testing (years)	Maintenance trials and diagnostic assessment?
Cape Town	Blue Route Mall, Tokai	9	Yes
	UCT New Engineering Building (NEB)	7	Yes
	UCT School of Economics	10	Yes
	UCT Irma Stern Museum	8	No
	Grand Parade, CBD	12	Yes
	MyCiti Bus Rapid Transport Depot, CBD	10	Yes
	Stor-Age Facility, Milnerton	10	No
	Hirsch's Appliances Milnerton	9	Yes
	Nirvana Residential Complex, Bloubergstrand	2	No
Gauteng	Wits First years' parking area, Johannesburg	13	Diagnostic assessment only
	Bosun Brick Pavers, Midrand	2	No

The Modified ASTM single-ring infiltrometer (Mod-ASTM) test

There is currently no universally accepted PICP infiltration test method. The most commonly adopted method appears to be the ASTM C1701/1701M: *Standard Test Method for Infiltration of In Place Pervious Concrete*, sometimes called the Single-Ring Infiltrometer Test (SRIT) because it only uses one ring as opposed to the Double-Ring Infiltrometer Test (ASTM D3385:2009) which is preferred for the measurement of soil infiltration rates (ASCE, 2018). There are, however, problems with the SRIT when used to measure infiltration rates in PICP. These include: leakage, marking of the surface, excessive water use, and the unacceptably long test time for partially blocked PICP. Most PICP testing in this project was carried out using ASTM C1701/1701M / SRIT with some minor modifications which was thus termed the Modified ASTM (Mod-ASTM) test (Figure 2).

FIGURE 2: *ASTM C1781 test apparatus (left) and Mod-ASTM test apparatus (right)*

The modifications included:

- The steel ring was replaced with a 500 mm long x 315 mm diameter unplasticized vinyl chloride (uPVC) pipe weighted down with small concrete blocks when in use.
- 10 and 15 mm head marks were made at the bottom of the ring to help guide the rate at which water was poured into the apparatus.
- The plumbers putty normally used to reduce water loss out of the bottom of the ring was replaced with a 10 mm neoprene foam strip glued to the bottom of the pipe.
- After experiencing unacceptably long test periods where it appeared that significant quantities of water were leaking out of the apparatus via the gaps between the pavers that could not be completely plugged with small neoprene pieces, the maximum testing time was limited to 15 minutes after which no further water was added. The timer was stopped when all the remaining water in the apparatus had infiltrated into the test spot. The total quantity of water infiltrated into the PICP was then determined by subtracting the remaining water determined with the aid of a measuring cylinder from the initial 18 L prescribed for the full test.
- ASTM-C1781-14a states that 3.6 L of water should be used for pre-wetting, however, when the Mod-ASTM test was carried out in combination with the Mod-SWIFT test, the latter was performed first which wetted the surface making the pre-wetting stage for the Mod-ASTM test redundant.

Otherwise, the test procedure followed the method described in ASTM C1701/1701M.

Determining surface infiltration rates using Modified SWIFT

The other test that was used to determine the PICP surface infiltration rate was the Modified Stormwater Field Test (Mod-SWIFT, Figure 3). The Stormwater Field Infiltration Test (SWIFT) infiltration capacity is normally determined by counting the number of bricks wetted by 6 L of water dropped through a distance of 60 mm from a bucket after a 40 mm diameter plug is pulled, and linking this to the possible need for maintenance (Lucke et al., 2015). Its strength lies in the reduced water requirement, its speed, and its ease of use. Its weakness is that pavers come in different sizes and shapes and counting fully-wetted bricks as per the method is tedious.

FIGURE 3: *Mod-SWIFT test apparatus (not situated on a PICP)*

In a bid to make the SWIFT test both more general as well as more informative, the counting of fully-wetted pavers was replaced with an approximation of the wetted surface area by assuming that it is roughly elliptical (circular if the surface is flat). Noting the constant ratio between an ellipse and a rectangle bounding it, the calculations were then further simplified by relating the wetted area to this rectangle. The infiltration rate could then be related to that measured by the Mod-ASTM through the use of Equation 1 determined from a plot of data points from previous PICP research conducted at UCT (Figure 4).

$$I = 2210 - 930\ \ln(a \times b) \qquad (1)$$

Where:

$I =$ Infiltration rate (mm/hr)

$a =$ Length of longest wetted section (m)

$b =$ Length of the longest wetted section perpendicular to a (m)

The test procedure for the Mod-SWIFT is similar to that for the SWIFT described by Lucke et al. (2015). The Mod-SWIFT was particularly helpful in the field when there was limited access to test water. The Mod-ASTM test was, however, preferred in the laboratory or where adequate supplies of test water were available to allow comparisons with published data.

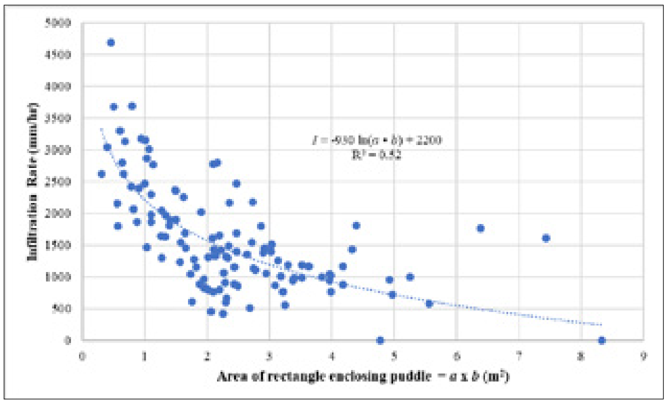

FIGURE 4: *Mod-ASTM infiltration rate versus representative wetted area for the Mod-SWIFT test*

The PICP maintenance trials

The long-term performance of PICP is determined to a large extent by its maintenance, particularly with respect to reducing the clogging process. There are effectively three types of maintenance: routine, restorative and reconstruction. Routine maintenance is the regular maintenance designed to identify and slow down the rate of clogging and potential structural failure (Woods Ballard et al., 2015). Restorative maintenance attempts to remove the material causing the clogging. Reconstruction is required when the PICP become so clogged – generally defined as a measured infiltration capacity of less than 250 mm/hr (ASCE, 2018; Hein, 2018) – that the only sensible remedy is to remove the pavers and the underlying bedding material, clean and reinstate them (Sehgal et al., 2018).

At the time the research was carried out, the only maintenance of PICP being carried out in SA was at a limited number of sites in Cape Town where the joints were regularly blown out to remove clogging material. Compressed air was directed along the joints and the dislodged material swept by a hand broom to the edge of the pavement from where it was collected. Gritstone that was removed with the gross pollutants from the joints was sieved, washed, and re-used for filling the joints. The joints were topped up by new clean gritstone where required. Attempts were made to investigate the maintenance performance of:

1. Blowing followed by sweeping (the current practice)
2. A street sweeper truck,
3. A vacuum truck, and
4. An industrial vacuum cleaner.

Unfortunately, it was not possible to secure street sweepers or vacuum trucks as they were being fully utilised over evaluation period, however, an effort was made to investigate the maintenance combination of the compressed air blower and a 2000 W wet/dry industrial vacuum cleaner – but this proved ineffective. Some researchers (e.g., Drake & Bradford, 2013; Nichols et al., 2014) contend that blowing followed by vacuuming is the most effective method to maintain PICP but it is likely that this requires a much more powerful vacuum machine than that was available for this project. On the other hand, Hein (2018) notes that if the vacuum is too powerful there is a risk of the bedding and/or pavers being lifted causing failure of the surface. In the end, maintenance trials were carried out at six sites in Cape Town (Table 1). The general procedure for the trials was as follows:

- Permission to perform maintenance trials was first obtained from the site owners.
- Mod-ASTM surface infiltration rates were conducted on the identified PICP test spots. These results were recorded as base infiltration rates.
- The test spots were surrounded by a shade-cloth fence to protect adjacent property or people from flying debris. The workers wore appropriate Personal Protective Equipment (PPE).
- Maintenance was performed on the test spot using a 700 kPa compressed air blower attached via a flexible hose to a steel 'wand' with an 8 mm nozzle. The minimum area of cleaned surface was 2 m x 2 m. The blown-out debris was blown to one side and collected for removal and/or recycling (in the case of the joint gritstone).
- The post-blowing and post-maintenance infiltration rates were then measured to determine the effectiveness of the maintenance.

PICP diagnostic assessments

Diagnostic assessments were performed on selected pavement test spots that did not show significant signs of surface infiltration improvement during the maintenance trials in a bid to understand where the clogging was taking place. The general procedure was as follows:

- The pavers were carefully lifted, and the joints and bedding inspected for signs of clogging.
- The infiltration rate through the bedding was determined using the Mod-ASTM test.
- The bedding was carefully scooped away to expose the upper geotextile or base course (no upper geotextile design). All observations were recorded. Another Mod-ASTM was carried out on the geotextile or base course as applicable.
- If the geotextile – if present – was clogged, a piece was carefully cut out and the underlying aggregates inspected – all the way down to the lower geotextile or sub-base as applicable.
- Once the location and type of clogging had been identified, the paving was reinstated taking care to compact each layer and fill the joints between the pavers with washed gritstone.
- The post-maintenance infiltration rates of the pavers were measured upon completion of the re-gritting.

Laboratory investigation into the link between the upper geotextile, different pavers, and clogging

Research in Australia, the USA, and SA suggests that fine material can propagate into the permeable pavement system and potentially clog any geotextile present (Fassman & Blackbourn, 2010; Biggs, 2016; Winston et al., 2016). The fine material originates from both the PICP surrounds as well as from within the pavement structure owing to the use of dirty aggregates and/or from their crushing under the impact of traffic. In a bid to better understand the potential for clogging in various different geotextile and paver combinations, accelerated laboratory experiments were designed and conducted in four HDPE test cells situated in the University of Cape Town (UCT) laboratory to investigate:

1. The link between different geotextiles and clogging with pavers installed (Thando Peyi, unpublished data; Joshua Blackshaw, unpublished data),
2. The link between the paver opening and clogging using the same geotextile throught (Thobani Mqadi, unpublished data), and
3. The link between different geotextiles and clogging without pavers installed (James Morritt-Smith, unpublished data).

TABLE 2: *Summary of laboratory experiments*

Experimental run	Test cell	Paver type	Geotextile
Experiment 1a	A	Permaflow®	Control (No geotextile)
	B		Fibertex F25® (Nonwoven, heat treated)
	C		Kaytech Bidim® (Nonwoven, non-heat-treated)
	D		Kaytech Kaytape® (Woven, non-heat-treated)
Experiment 1b	A	Aquaflow®	Control (No geotextile)
	B		Fibertex F25® (Nonwoven, heat treated)
	C		Kaytech Bidim® (Nonwoven, non-heat-treated)
	D		Kaytech Kaytape® (Woven, non-heat-treated)
Experiment 2	A	Aquaflow®	Kaytech Bidim® (Nonwoven, non-heat-treated)
	B	Aquapave®	
	C	Permaflow®	
	D	Permealock®	
Experiment 3	A	Not used	Control (No geotextile)
	B		Fibertex F25® (Nonwoven, heat treated)
	C		Kaytech Bidim® (Nonwoven, non-heat-treated)
	D		Kaytech Kaytape® (Woven, non-heat-treated)

The first experiment was performed twice, once with Aquaflow® and once with Permaflow® pavers at slightly different loading rates – all with three different geotextiles plus one control without any geotextile to explore the impact of the different geotextiles. The pavers are both commonly used in South Africa. The three geotextiles types were chosen to represent: a non-woven heat-treated (Fibertex F25®), a non-woven non-heat-treated (Kaytech Bidim A®), and a woven non-heat-treated (Kaytech Kaytape S120®) geotextile. Although Inbitex® – a nonwoven heat-treated geotextile – has been extensively used in SA, it was unavailable at the time of the research so Fibertex F25® was used as a substitute as it has similar properties. The second experiment was performed using four different pavers (Aquaflow®, Aquapave®, Permaflow® and Permealock®) commonly used in SA, each laid on a non-woven, non-heat treated geotextile – Kaytech Bidim A1® – to explore the impact of different joint openings on clogging. The third experiment was designed similarly to Experiment 1 but with no pavers and relatively higher sediment loading rates. The aggregates laid in the PICP cells were washed before being laid and compacted. In Experiments 1 and 3, Cell A was not supplied with a geotextile to serve as a control. A summary of the laboratory experiments is presented in Table 2.

RESULTS

Clogging typology

Four types of PICP clogging (Figure 5) were identified in the course of the diagnostic assessments:

- Type I clogging – the most common type – is when fine material fills the joints, typically the first 20 to 30 mm depth from the surface.
- Type II clogging takes the form of a sediment 'wedge' on the bedding layer immediately under the joints and usually looking like a silhouette of the paving pattern.
- Type III clogging is when the bedding layer and the top of any geotextile have been filled with sediment.
- Type IV clogging sees sediment throughout the full depth of the PICP layers (complete failure).

These are also in the rough order of occurrence – with Type I clogging being not only the first to take place but is also the most common by far, while Type IV clogging is the least common although it can be 'built in' during construction.

Clogging and age

All PICP surface infiltration rates start off extremely high – typically between 7000 and 20,000 mm/hr (ASCE, 2018), but they rapidly decrease with the age of the installation. Some sites' surface infiltration rates however drop at a faster rate than others (Borgwardt, 2015). For example, Nguyen *et al.*, (2022) reported PICP still recording significant infiltration capacity (800 mm/hr) after 20 years in operation, while other sites may fail within days as a consequence of poor design, construction and/or (lack of) maintenance. The gritstone placed in the gaps between the pavers acts like a filter trapping fine particles. While this is of considerable benefit for downstream water quality, these fine particles ultimately clog the pavement (Type I clogging), unless removed. The particles can only go in one of two directions: i) through physical removal onto the surface e.g., through air blowing and subsequent sweeping and/or vacuum removal, or ii) by being driven further into the layers where they tend to collect at the base of the openings between the pavers where they form a 'wedge-shaped' mass that inhibits infiltration (Type II clogging). Traffic movement – particularly on poorly restrained pavers that can move laterally – combined with runoff can redistribute some of the fines into the bedding layer and clog any geotextile present (Type III clogging) (Mullaney & Lucke, 2014). Ultimately, fine particles may find their way into the base layers where they fill the openings and reduce the overall porosity and permeability (Type IV clogging). All of this takes time.

FIGURE 5: *Different types of clogging: I (top left), II (top right), III (bottom left), IV (bottom right)*

Given the clear link between the clogging mechanisms and time, it would be expected that the field research would show a clear trend linking age with lower infiltration rates. Unexpectedly, this was not the case. The research showed very little correlation between age and measured infiltration rates for the eleven sites that date back to the Wits parking area which had been in operation for 13 years at the time of testing. This suggests that other factors are far more significant than pavement age in accounting for the deterioration of PICP infiltration performance.

Clogging and Run-on Factor (RoF)

The Run-on Factor (RoF) is the ratio of the impermeable area that drains to the PICP to the area of the PICP itself. The higher the RoF, the more the runoff volume is generated and the greater the quantity of sediment deposited on the PICP per storm. For this reason, many authorities recommend limiting the RoF – for example, a RoF of 2 (ASCE, 2018; Interpave, 2018), or 3 (WDNR, 2021), however, much higher RoFs have been reported, e.g., 27.6 (Tirpak *et al.*, 2021). Clearly, a RoF = 0 (no contribution from impermeable surfaces) is likely to result in the best performance.

It was expected that the higher the RoF, the low the infiltration rates will be due to surface clogging. However, no particular pattern was evident in the relationship between the RoF and the infiltration rates measured in the field. Thus, it can be concluded that RoF alone also does not fully explain the clogging rate.

Clogging and paver type

Various paver types are available on the market. Tests carried out in the UCT laboratory showed that the rate of clogging largely correlates inversely with the void ratio i.e., the larger the joint openings, the slower the clogging rate.

Clogging and the upper geotextile

Geotextiles are geosynthetic fabrics that are used in pavements to separate, filter, drain, and protect the subgrade. The most commonly used upper geotextile seen in the field investigations was Inbitex ® – a heat-bonded non-woven geotextile – installed between the bedding layer and the base layer. In most instances, there was no sign of clogging. Where there was evidence of clogging, this was associated with heavy traffic loading and movement of the pavers. Furthermore, the geotextiles that were installed in high-traffic situations, even when unblocked, were frequently found to be severely damaged even after only a relatively short period (e.g., eight years) of the PICP in operation, and thus unlikely to be fulfilling any function in the system. On the other hand, geotextiles installed in parking bays were generally intact even after more than 13 years of service. Research carried out in the laboratory showed no evidence whatsoever of geotextiles clogging, but this may have simply been because of the experimental method and/or material used.

Instances of both clogged and punctured upper geotextiles have been reported in the literature (Pezzaniti et al., 2009; Woods Ballard et al., 2015). This research suggests that geotextiles can be confidently used most of the time but should be avoided in high-trafficked sections – where, in any case, any type of PICP should probably be avoided.

Clogging and environmental factors

Since clogging in PICP is largely due to the trapping of sediment, it was unsurprising that there was a strong correlation between the position of the PICP and clogging. Typical 'danger' areas are proximity to unstable slopes, overhanging trees, planters of various shapes and sizes, or sources of wind-blown sand.

Clogging and poor paver installation

If pavers are not properly installed with adequate edge restraint, they will move – particularly if subject to high turning movements near busy intersections. This allows sediment to easily enter the widened gaps between the pavers from where it is 'worked' under the pavers layer and into the bedding layer. If a geotextile is present, Type III clogging is likely. If not, the PICP will eventually fail with Type IV clogging.

Clogging and maintenance

Like any pavement, PICP must be maintained if it is to provide the desired level of serviceability over a long period of time. It was apparent from the site investigations that this – at a minimum – requires:

- Immediate attention to any structural issues such as widening openings between pavers, rutting, broken pavers etc.
- Keeping the surface as clean as reasonably possible.
- Ensuring that the gritstone is regularly 'topped-up' to trap sediment before it gets into the underlying layers.
- Periodically blowing out the contaminated gritstone (Type I clogging) and replacing it with clean gritstone.
- Since some material will inevitably find its way to the bedding, it will eventually become necessary to temporarily remove the pavers and bedding, clean them, and replace them – taking care to add new (clean) gritstone in the voids between the pavers.

THE SA GUIDELINES

Input from the literature review, the collection of data from existing PICP installations, the laboratory investigations into the role of geotextiles and pavers in possible PICP clogging, and the collective wisdom of the specially created PICP Working Group that eventually included 28 professionals and 31 students – all overseen by the WRC Reference Group of six – culminated in the development of two documents: '*Guidelines for Permeable Interlocking Concrete Pavements (PICP) in South Africa (TT 913) – Volume 1: Clogging in Permeable Interlocking Pavement (PICP)*' (Monyake & Armitage, 2023), and '*Volume 2: Guidelines for the Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement (PICP) in South Africa*' (Armitage & Monyake, 2023).

The guidelines cover the following topics:

1. **Introduction**: the purpose of the document; supporting documents; general description; main application; and the three distinct phases involved in PICP systems.
2. **PICP Design**: 2.1 Introduction: how PICP may be recognised; how it works; site considerations; proprietary computer packages; areas where it should ideally not be used; the importance of limiting the RoF. 2.2 Preliminary Design: optimal sites; physical inspection; determination of the likely hydraulic loading; draft layout drawings; geotechnical investigation. 2.3 Structural design; standards and guidelines to follow; paver selection; selection of aggregates; selection of geotextiles; edge constraints; link to hydraulic loading; design life. 2.4 Hydraulic Design; data collection; the determination of the Water Quality Volume (WQV); the significance of the different joint design offered by competing pavers; the joint gritstone; the bedding layer; the upper geotextile; the 'choke(r)' layer if required; the significance of high water table and subgrade on PICP design; underlying base and subbase layers; the relationship between water table and subgrade and the potential for infiltration; how to handle sloping ground; the lower geotextile / geomembrane; underground services. 2.5 Additional design considerations: water table; leaves and pollen; sediment traps; building structures; intersections; RoF; Life-Cycle Cost analysis; Maintenance Plan.
3. **PICP Construction**: 3.1 Workflow plan. 3.2 During construction: standards; aggregates and their storage; handling of geosynthetics and drainage pipes; washing the aggregates before use; compaction of the subgrade; laying of geosynthetics; compaction of the stone layers; protection of the pavers in-between construction activities; handling vehicular traffic during construction; inserting the gritstone into the paver joints; testing; monitoring of adjacent areas to ensure they do not impact the PICP; details of the installation and approved Maintenance Plan. 3.3 During the Defects Liability Period: checking for sources of dirt; the addition of more gritstone; testing for both structural integrity and hydraulic capacity.
4. **PICP Maintenance**: 4.1 Introduction; Maintenance Plan; classification of maintenance types; the inspection report. 4.2: Routine maintenance: inspection; types of clogging; testing; repair; trimming of vegetation; cleaning hydraulic structures; maintenance techniques available; gritstone; documentation. 4.3 Restorative Maintenance: maintenance techniques available; gritstone; disposal of contaminated material; documentation; reconstruction.

The **Appendices** include: the Modified ASTM single ring infiltrometer (Mod-ASTM) test method; the Modified SWIFT (Mod-SWIFT) test method; a template for Details of PICP installation; a template for PICP testing; Instructions for diagnostic assessments; and a template for a PICP inspection report.

It is a 'living document' – meaning that it can be periodically revised to account for new understanding of the performance of PICP in field and users are encouraged to communicate with the principal author in this regard. Overall, it is hoped that its adoption will lead to an improvement in the performance in PICP that will, in turn, increase the resilience of stormwater drainage systems to the impacts of development.

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