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THE DESIGN, CONSTRUCTION AND EVALUATION OF PERMEABLE PAVEMENTS IN AUSTRALIA

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ABSTRACT

Permeable pavements provide a sustainable engineering solution to many common urban engineering problems but require new approaches to design, materials selection and construction. After listing the advantages and limitations of permeable pavements, the paper describes the development and implementation of a new design methodology for permeable pavements specifically tailored to Australian conditions which is based on research conducted both in Australia and overseas. The construction requirements implicit in implementing such designs are discussed with particular reference to materials selection and in-service performance. Methods for characterising such materials are then summarised. Finally, the utility of permeable pavements is critically assessed by reference to in-situ measurements of the performance of a series of permeable pavements in New South Wales and South Australia which are currently carrying traffic and which have served for periods of 8 to 10 years.

INTRODUCTION

In urban catchments, pavements can account for up to about 25% of impermeable surfaces i.e. pavements are a major generator of runoff. One way to control this runoff is to use permeable pavements. Although by training engineers are customarily inclined to make all pavements impermeable, nevertheless permeable paving offers significant benefits over conventional pavements in terms of sustainability, environmental impact and project cost. Permeable pavements can achieve the following objectives (Shackel, 1996a, 1996b, 2005).

1. To reduce the amount of rainfall runoff from pavement surfaces and, thereby, to eliminate or minimise the extent of the stormwater drainage system. As noted below this can lead to substantial savings in the overall project costs.
2. To reduce the size or need for rainwater retention facilities in roadworks by using the pavement itself for retention. This improves land use.
3. To reduce or avoid downstream flooding.
4. To recharge and maintain aquifers and the natural groundwater.
5. To trap pollutants that would otherwise contaminate groundwater or drainage systems.
6. To assist in the biological decomposition of hydrocarbon contaminants.

Permeable surfacings include porous asphalt and concrete where water passes through the pores of the surfacing itself or Permeable Interlocking Concrete Paving (PICP) where openings or joints between individual interlocking concrete pavers facilitate infiltration. Although often more costly as a surfacing, PICP offers some advantages over porous asphalt and concrete. These include achieving high infiltration rates which are more than sufficient to handle the design storms encountered across Australia, and that clogging is easily remedied. Whilst many of the principles discussed below apply to all forms of permeable pavement, the main emphasis in this paper is on PICP. A cross-section through a typical PICP is shown in Figure 1. This figure shows pavers provided with opening or drainage voids at intervals along the joints. These voids are filled with a uniform 2 – 5 mm aggregate to facilitate rapid infiltration of rainfall. The same aggregate can be used as a bedding material for the pavers.

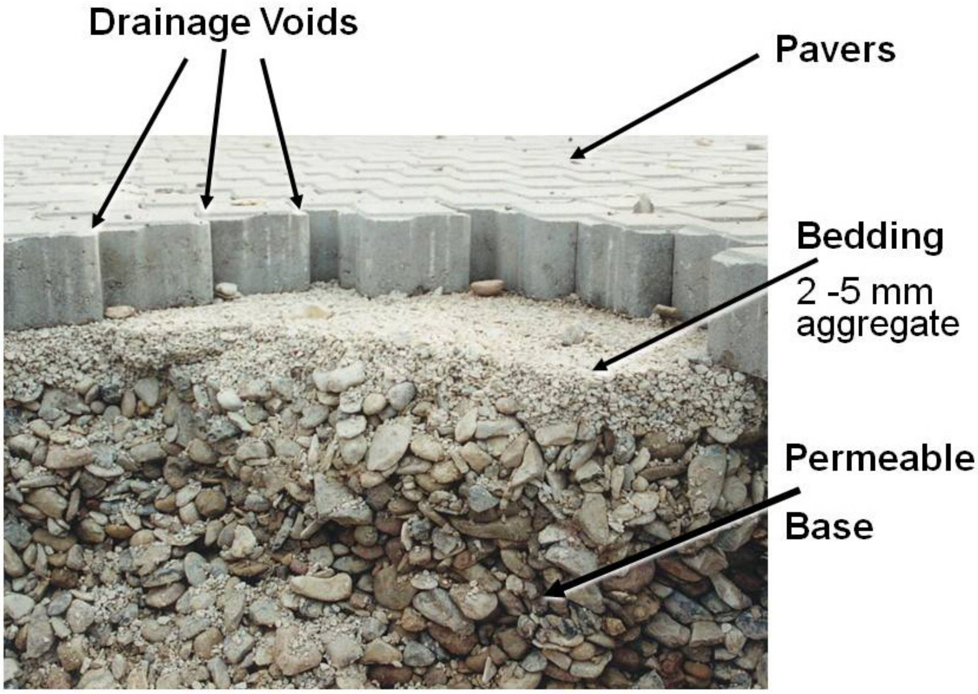

Figure 1: Typical PICP Cross-section

PICP concepts only began to emerge in Germany and Austria some 25 years ago but subsequently spread rapidly throughout the UK and Europe, Australia, Japan, the Americas and South Africa to become a viable option for sustainability worldwide. Originally in Europe, permeable paving was seen principally as a means of flood mitigation and control. This concept remains a powerful argument for using permeable paving in highly urbanised societies such as Australia where urban consolidation is placing ever increasing demands on existing and often barely adequate stormwater infrastructure.

Almost invariably, the uptake of permeable paving has been a reaction to regulations for achieving sustainability and managing the environment. For example, the UK concept of Sustainable Drainage Systems (SUDS) and its Australian equivalent, Water Sensitive Urban Design (WSUD) both aim to manage stormwater and pollution at either the site level or on a regional basis (e.g. Pratt, 2001; Argue, 2004). As such they are referenced by planning guidelines and drainage regulations and provide a rational framework for incorporating permeable paving into urban design. Pollution control has also provided a strong incentive for adopting PICPs. In the USA, the Environmental Protection Agency (USEPA) places its main priority on controlling stormwater pollution and has required developers of projects greater than 0.4 ha (1 acre) in size to apply for permits specifying Best Management Practices (BMP) for stormwater runoff management. Structural BMPs approved by the USEPA include permeable paving (USEPA, 2007).

Engineers often perceive cost to be a major obstacle to adopting PICP. Although the cost of a PICP surface may be greater than, for example, an asphalt surface, experience in the Northern hemisphere and recent studies in the UK have shown that PICP gives significantly lower initial and whole-of-life project costs than asphalt or cast in place concrete pavements (Interpave/Scott Wilson, 2006). This is principally because of the reduction or elimination of sub-surface drainage infrastructure. Moreover, concerns about the long term maintenance costs of permeable paving due to clogging have largely been allayed by tests in Europe, North America (e.g. James and von Langsdorff, 2003; Borgwardt 2006) and, as noted below, Australia. These indicate that permeable paving can achieve service lives of 15 to 25 years without the need for anything other than routine maintenance.

DESIGN REQUIREMENTS

Permeable pavements must be designed not only to carry traffic but also to manage runoff, infiltration, pollutant transport and, where appropriate, water harvesting. They, therefore, present new technical problems and challenges to pavement designers that are not covered by conventional pavement design methods. In particular the selection, specification and characterisation of the materials used in the surface, base and sub-base of permeable pavements require designers to modify existing design methodologies to facilitate water movement through the pavements whilst maintaining satisfactory serviceability under traffic in saturated conditions and to provide adequate water storage where required. Essentially, as shown in Figure 2, engineers need to go through three design stages. These comprise:

1. The choice of the pavement surfacing, cross-section and materials.
2. A hydraulic analysis leading to the design of the thicknesses of materials needed for water management
3. A structural analysis of the pavement thicknesses needed to support traffic.

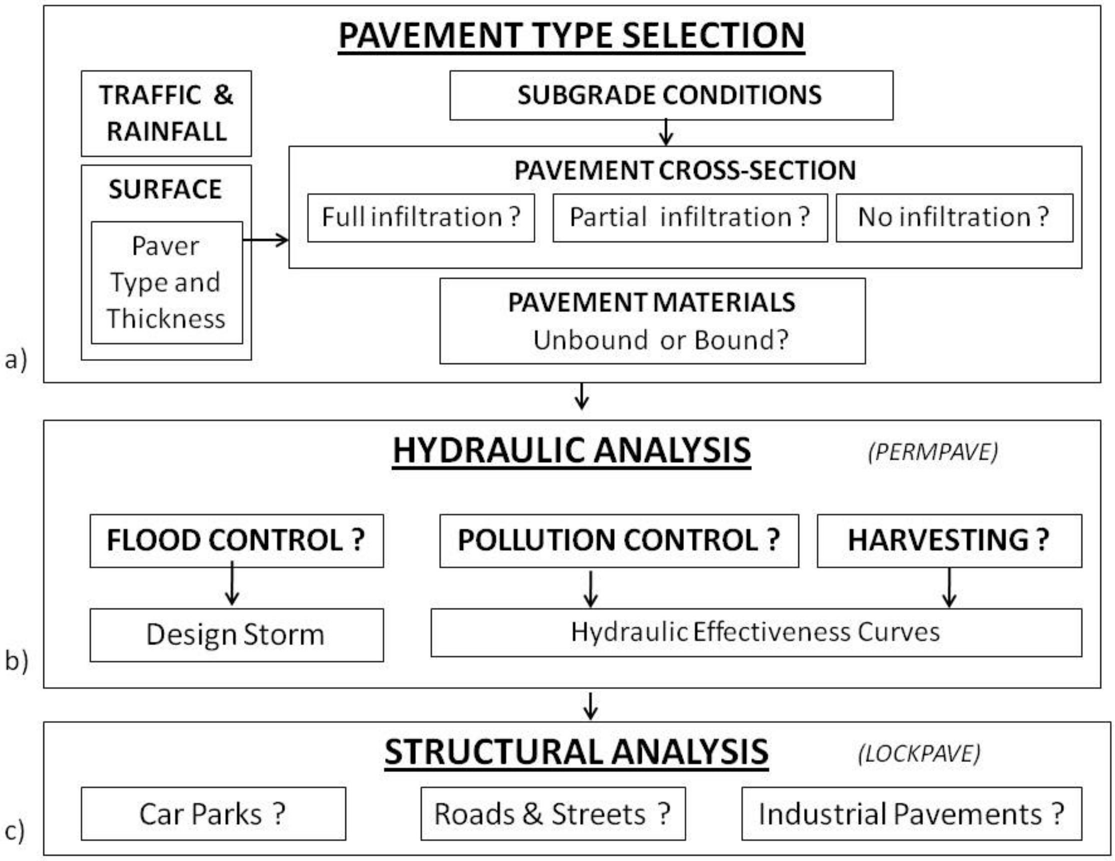

Figure 2: Overview of Permeable Pavement Design

It will be seen that the design of permeable pavements involves one additional step not considered in conventional pavement analysis i.e. stormwater management. Unfortunately the water management procedures required here are often unfamiliar to pavement engineers. For this reason, in 2006 the Concrete Masonry Association of Australia commissioned the School of Natural and Built Environments at the University of South Australia in conjunction with the author to develop new software called PERMPAVE for permeable pavements. This was published in 2007 and dovetailed with existing structural design software for concrete segmental paving, LOCKPAVE, to provide an integrated approach to designing permeable interlocking concrete pavements. Details of these programs have been given elsewhere (Shackel and Pezzaniti, 2009, 2010; Shackel, 2000). These programs draw on the extensive research that has been conducted into both the structural and water management characteristics of PICP in Australia (e.g. Shackel, 1996a, 1997; Shackel at al 1996, 2000; Urban Resource Centre, 2002) and overseas as well as on-going local research into PICP basecourse materials (Shackel et al, 2001; Zhuge and Hazell, 2007; Oeser et al, 2009).

Pavement Type Selection

Choice of surfacing

Research has shown that the concrete pavers which form the surfacing of PICP differ in their structural capacity (Shackel et al, 1996, 2000) and their ability to infiltrate water (Borgwardt, 2006). In the case of structural capacity the prime determinants of performance are the paver shape, thickness and laying pattern (Shackel, 1996a; Shackel et al, 1996, 2000). Published guidance for paver selection for performance under traffic has long been available (e.g. Shackel, 1996a). For water infiltration there are data acquired from both laboratory tests (Shackel, 1997; Shackel et al 1996, Urban Water Resources Centre, 2002) and in-situ infiltration measurements on PICPs that have been in service for periods of up to about 20 years (Borgwardt, 1997, 2006). It is possible to classify pavers into five groups in terms of infiltration and to rank their suitability for traffic. These classifications (Shackel, 2006) have been made an integral part of the design methodology and software.

Subgrade conditions

The subgrade soil determines the type of pavement cross-section that is required to manage both the structural response to traffic and water management requirements. The possible cross-sections are shown in Figure 3. Contrary to some engineering misconceptions, PICP have been successfully constructed over all types of subgrade and not just over granular materials. Where the subgrade is a non-cohesive granular material it is usually possible to infiltrate fully all the design rainfall. However, for a cohesive clay subgrade only a small fraction of the stormwater runoff can be expected to infiltrate the soil i.e. only partial infiltration is feasible. In some cases, such as where the subgrade soil is contaminated, expansive or saline or where local regulations do not permit infiltration, an impermeable liner must be placed between the pavement and subgrade so that no infiltration is possible. In the cases of either partial or no infiltration, the pavement's main function is to detain the water temporarily and then to allow it to efflux via a carefully sized outlet pipe to the stormwater sewers at a rate chosen not to overload these facilities. Here, both the storage volumes of the permeable basecourse and bedding materials and the size of the drainage outlet must be designed together.

Choice of pavements materials

Criteria for the base and sub-base materials for permeable pavements have been discussed elsewhere (Shackel, 1997, 2006; Shackel at al,1996). Suitable materials include unbound granular base, cement treated base, lean concrete and porous asphalt. The most widely used bases for permeable pavements have been unbound granular materials although recent Australian research has shown that cement bound materials offer promising alternatives (e.g. Zhuge and Hazell, 2007; Oeser et al, 2009).

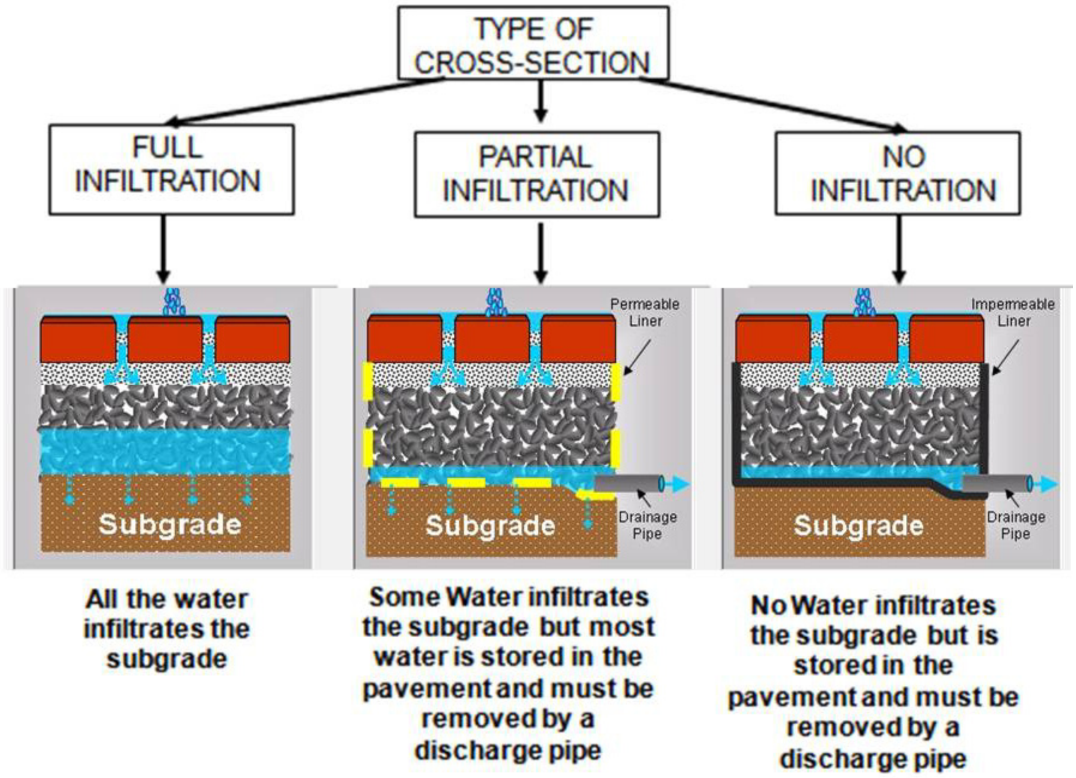

Figure 3. Permeable Pavement Cross-sections

Hydraulic Analyses

The hydraulic analyses are implemented by the PERMPAVE software referenced above. The important tasks implemented by this program are:

1. To calculate the capacity of the pavement to manage design rainfall events by infiltration to the subgrade or to the storm sewers i.e. Flood Control.
2. To determine the quality of the effluent leaving the pavement after removing pollutants i.e. Water Quality.
3. To determine the extent to which is it possible to store and reuse the water i.e. Water Harvesting.
4. To design the size of any drainage pipes connecting to the storm sewers.

Permeable pavements are capable of meeting multiple water management objectives. As described in detail elsewhere (Shackel and Pezzaniti, 2009, 2010) the PERMPAVE program operates in a step-by-step sequential mode for each of the flood, water quality and harvesting/reuse modules. Furthermore, each module operates independently of the others and hence, if a design requires a solution to achieve more than one objective, each of the relevant modules can be used separately.

For flood control the design storm approach as incorporated in standard design procedures (Engineers Australia, 1999; Argue and Pezzaniti, 2005) is used. However it is not feasible to design for water quality and harvesting using some particular nominated storm. Rather the pattern of rainfall needs to be modelled (simulated) over a substantial period of time. This can be achieved in an efficient manner by using the concepts of hydrological effectiveness curves developed by Argue and Pezzaniti (2005). Hydrological effectiveness curves are a representation of the performance of a system (incorporating storage and discharge features) to manage inflows such as runoff from a specified catchment. A continuous water balance simulation analysis is carried out using historical rainfall data for a particular geographical location. In most cases around 20 years of 6 minute interval rainfall data are needed to generate the hydrological effectiveness relationships. This is because, for small catchments, a short time step (6 min) simulation is necessary to achieve reliable performance information.

This means large volumes of data are necessary to produce realistic outcomes. Consequently it is not feasible to provide a generic solution that can be used anywhere where water quality and harvesting are of interest. Rather, the program needs to be rewritten for each country or region where it is to be used and where the appropriate local long-term rainfall records already exist. To date this has been done for PICP only for Australia and South Africa.

Flood Control

Briefly, the design storm approach involves the use of local average design storm intensity bursts for a particular Average Recurrence Interval (ARI). A storm temporal pattern is applied to the average storm intensity to provide a rainfall distribution pattern over a period of time. Such data are stored within the software for specified Australian geographical locations. Design inputs include the area of the permeable paving, the hydraulic conductivity of the surfacing, any impervious area draining to the permeable paving, the permeable paving storage, the saturated hydraulic conductivity of the subgrade, the drainage outlet discharge characteristics and antecedent conditions (e.g. is the pavement already part-full with stormwater?).

A key function of the flood control module is the determination of the storage required to achieve the maximum peak discharge flow rate permitted from the permeable paving system. The maximum peak discharge is set by either specifying the allowable peak flow rate or an equivalent runoff coefficient. When selecting a cross-section that includes a pipe discharge with or without infiltration to subgrade, the analysis determines the *smallest* pipe size and storage volume required to achieve a maximum discharge from the pavement that is just less than that set by the user. Importantly, the discharge pipe diameter as calculated by the program should not be increased or reduced.

Water Quality

The water quality module uses the hydrological effectiveness relationships to assess the water quality improvement provided by the pavement. The program determines the minimum volume required to achieve some target reduction in pollution load. Given that the predominant mechanism for removing pollutants from the runoff flow is mechanical filtration, a simple pollutant removal algorithm is included, based on typical runoff pollutant event mean inflow concentration and reduction rates. The analysis combines the hydrological effectiveness relationships with inflow concentration removal fraction to produce an overall reduction in terms of average annual pollution load (e.g. kg/yr).

Where there is a discharge pipe the user will need to specify a constant discharge rate for pipe efflux. The discharge associated with infiltration is determined by the program using subgrade hydraulic conductivity. For installations with full infiltration discharge, 100% pollutant removal is assumed and only the surface excess flow is assumed to be untreated. For installations with both infiltration and pipe discharge only the proportion of pipe flow is considered to be treated.

Water Harvesting

The water harvesting module utilizes similar analysis techniques to those discussed above for water quality. The objective of this analysis is to determine the storage volume required to meet a nominated water demand. Three key inputs are required for the analysis. They include a constant daily demand rate (L/day), the average annual rainfall, and the storage voids ratio.

Determining the size of storage can be subjective and although supply for a given demand can be achieved it may not be necessarily the most appropriate or economical solution. With most storage systems there is a point where the return (supply) for a unit increase in storage will diminish. There are many factors that need to be considered. However, establishing storage based on diminishing rate of return approach is one option. The software analysis determines two storages, one based on a diminishing rate of return and the other based on achieving the total demand.

Design for Traffic

It is necessary to check that the thickness chosen for water management is also adequate to carry traffic. This is done by running the LOCKPAVE structural design module which forms part of the overall design process shown in Figure 2.

In conducting the structural analysis it is important that the designer recognise that the pavement sub-structure will often be fully or partially filled with water. Studies of basecourse materials for PICP by the author (Shackel et al, 2001) have shown that, at high saturations, the resilient moduli of granular materials are typically only about half the values measured at normal test saturations. This needs to be considered during design.

The structural and hydraulic analyses often give different design thicknesses. The greater of these is adopted as the final design.

CONSTRUCTION OF PERMEABLE PAVEMENTS

Construction techniques for permeable pavements differ little from the construction of conventional pavements except for the specifications that need to be applied to the permeable surfacing and to the base and sub-base materials

Surfacing Requirements

Not all types of PICP surfacing offer the same levels of in-service performance in terms of water infiltration, structural performance under traffic and ease of maintenance.

Water Infiltration

When tested new almost every type of paver for PICP will yield infiltration rates that are more than adequate to accept any rainfall event likely to be chosen for design in Australia. However, in-situ measurements on PICP which have been in service for several years (e.g. Borgwardt, 1997, 2006) show that, because of progressive clogging, the in-service values of infiltration reach equilibrium values after about 6 years which are much less than those measured on new paving. The reduction in infiltration depends on how the paver admits water through the surfacing. In this respect, pavers that are suitable for vehicular traffic can be classified into 3 groups:

1. Pavers which have openings along the joints. These openings are filled with a uniformly graded aggregate (2-5 mm) and act as vertical drains e.g. see Figure 1.
2. Pavers that have wide joints between each paver and its neighbours. These joints are filled with fine aggregate and allow water to penetrate the surface.
3. Pavers that are made of porous concrete which allows water to infiltrate through the pavers themselves.

In-situ measurements broadly indicate that pavers provided with drainage voids and openings achieve the highest long-term values of infiltration whilst those made from porous concrete give the least infiltration (Borgwardt,1997, 2006). This needs to be considered during design to ensure that the pavement can accept the design rainfall.

Structural Performance

The structural performance of any paving system depends on the paver shape, thickness and laying pattern. Structural tests of permeable pavers (Shackel et al, 1996, 2000, Urban Water Resources Centre, 2002) have confirmed these basic principles. In general pavers which have dentated shapes perform better than pavers that are rectangular. Where traffic is to be carried the use of herringbone patterns is recommended over all other patterns. For lightly trafficked pavements, such as car parks, the minimum recommended thickness of paver is 60 mm but for roads and industrial pavements a minimum thickness of 80 mm is required.

Ease of Maintenance

As noted elsewhere in this paper most of the particulate pollutants in PICP are trapped within the upper 20-30 mm of the materials filling the drainage opening and joints or, in the case of porous concrete pavers, within the concrete itself. Importantly, it has been shown that the infiltration capacity can largely be restored by removing and replacing the top 30 mm of the drainage material in the paving joints and drainage openings (James 2002, James and von Langsdorff, 2003) using conventional street vacuum sweeping equipment. In the case of porous concrete, hot water jetting and vacuum cleaning is often required (Dierkes et al., 2002; Urban Water Resources Centre, 2002). While some authorities in the USA recommend routine sweeping of PICP up to three or more times a year, experience in Europe and Australia suggests that such frequent maintenance is often unnecessary. In this respect many pavements have performed adequately for periods of 10 to 20 years without systematic cleaning. In addition, the area of paving constructed is typically dictated by such operational requirements as the length and width of a street or parking area and this is normally much greater than the minimum area need to control runoff and infiltration. Accordingly, the effects of clogging are normally much less severe than might otherwise be expected.

Basecourse and Sub-structure Requirements

In both the USA and UK it is common to specify uniformly graded materials for the basecourse of permeable pavements. These are similar to rail ballast with a maximum particle size of 40mm for base and 80mm for sub-base. The rationale for choosing such materials is that they have high void ratios and therefore can store large volumes of water within a given pavement thickness. To date such materials have only been used in pavements carrying very light traffic such as car parks. For roads and streets the use of such coarse uniform materials are unlikely to provide adequate service under heavy traffic. Whilst there has been limited use of normal well-graded granular road base in PICPs in Canada, the USA and Australia such pavements have only been in service for very short periods of time and their long term performance is unknown. For this reason the author initiated laboratory studies of well-graded PICP base materials in the 1990s. These studies are ongoing but have indicated that a good compromise between permeability and resilient modulus can be achieved with relatively minor changes to traditional gradings for dense graded road base (Shackel et al, 2001). The work has also shown that it is possible to manufacture cement treated base that may be suitable for PICPs (Oeser et al 2009).

Some American reports (e.g. Smith, 2001) have recommended that, during construction of a PICP, the subgrade be left uncompacted so as to facilitate infiltration. Clearly this is not conducive to good performance under traffic and normal compaction standards for the base, sub-base and subgrade should be rigorously applied.

IN-SERVICE PERFORMANCE OF PERMEABLE PAVEMENTS

Permeable pavements slowly clog over time because PICPs retain up to 90% of solids suspended in the water infiltrating the pavements (Urban Water Resources Centre, 2002). Field monitoring of PICPs (James, 2002; Borgwardt, 1997; 2006) has confirmed that the infiltration capacity of permeable pavements decreases as the amount of oil, grease and fine organic and inorganic matter accumulates within the aggregate filling the joints or drainage openings in the surface. This needs to be considered in the design of PICP when choosing a design rate of infiltration of water through the surface.

To study the effects of clogging and to assess the likely need for maintenance in PICPs a series of infiltration tests were conducted in NSW and South Australia on pavements that had been in service for periods between 8 and 11 years. These pavements had performed well over time without being subject to any systematic maintenance. The objectives of the tests were to assess a wide range of pavements using in-situ tests to measure their current infiltration rates, to examine clogging of the jointing materials, to evaluate the effects of sweeping the pavement surface and to assess the design implications of the in-service performance of the pavements.

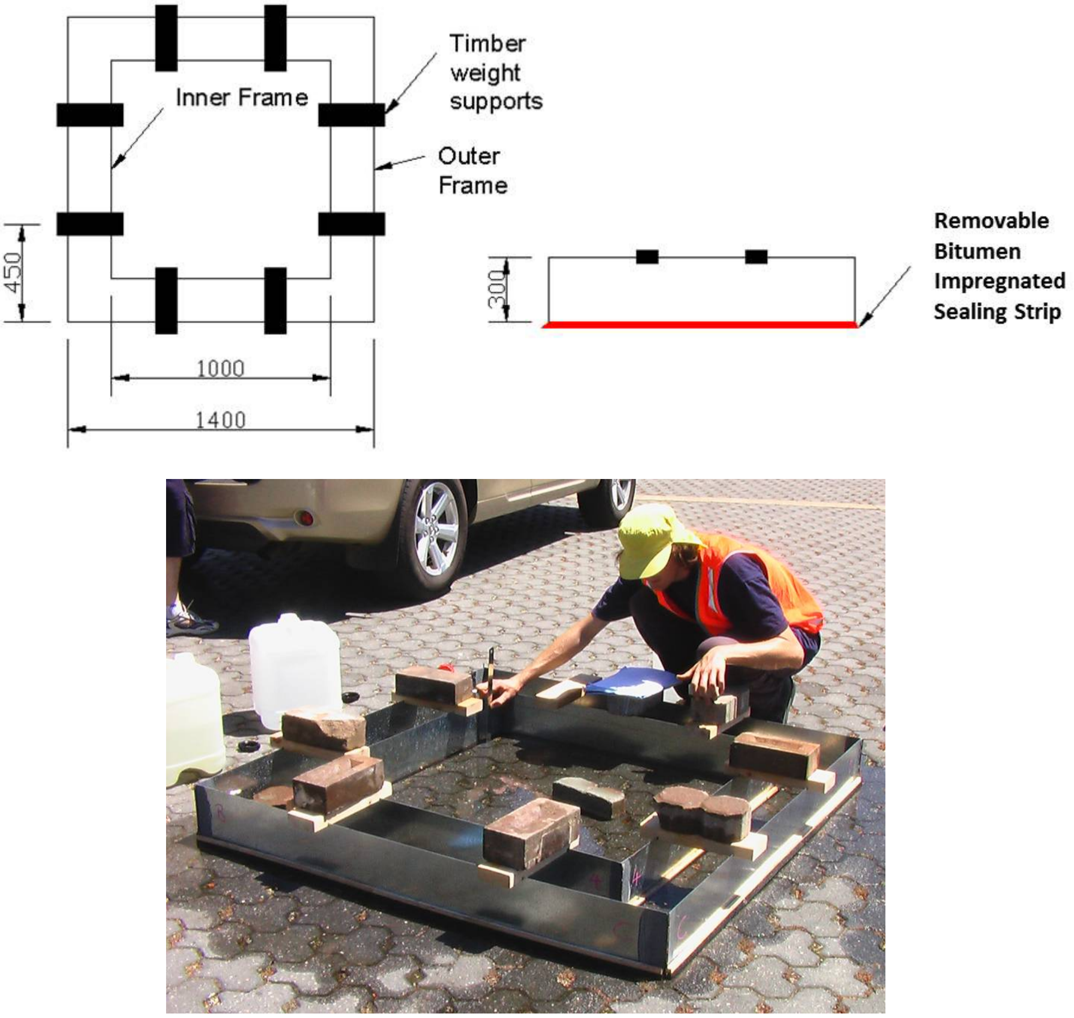

Figure 4. Double Ring Infiltrometer (all dimensions in mm).

Infiltration measurements were made using a double-ring infiltrometer (Figure 4). The test procedure was based on Australian Standard AS4693.5–2004. Details have been given elsewhere (Shackel et al, 2010). In general, the paving was tested "as found" without any attempt to clean the surface prior to infiltration measurements. In all cases, before measurements commenced, the surface was flooded with water. Repeated measurements were made at each test location to ensure that the tests were conducted under saturated conditions. The infiltration test results are summarised in Table 1. In one pavement laid without jointing materials the infiltration rate was too high to be measured accurately. Other tests were subsequently found to have been conducted over buried services. The data summarised in Table 1 exclude these results.

Six permeable pavements selected from more than 100 candidate PICPs were tested in New South Wales. A further three pavements were selected for testing in South Australia. All of the pavements had granular basecourses except for the Sydney Sports Ground paving which had a recycled concrete basecourse overlain with a thin aggregate capping. The pavements included pedestrian areas, car parks, roads and residential streets. All of the pavements used pavers with openings located along the paving joints (e.g. as shown in Figure 1) except two in South Australia which had widened joints to infiltrate stormwater runoff. Unfortunately, these joints had been left unfilled to facilitate a high infiltration capacity and, consequently, there was little or no structural interlock between the pavers. This is not accepted or good practice for PICP. Accordingly, the results from the pavements with unfilled joints, although published elsewhere (Shackel et al, 2010), are not included in the test summary given as Table 1 or discussed further here. With one exception (Shackel and Mearing, 2003) none of the pavements in Table 1 had been tested before. The pavements all carried vehicular traffic ranging from cars and service vehicles to normal road traffic and had been in continuous service up to the time of testing in early 2009

Table 1: In-situ Measurements of Infiltration

PAVEMENT TYPES AND LOCALES	DATE	PAVER TYPE	INFILTRATION TEST LOCATION	INFILTRATION RATES	
				mm/h.m^2	l/s.ha
PUBLIC SPACE + VEHICLES Olympic Park, Homebush, Sydney	March 1998	80 mm Eco-Trihex	Recently swept area under trees along Olympic Boulevard	282 - 343	784 - 952
			Approach to station – bottom of slope between trees	176 - 229 183 - 246	490 - 635 508 - 683
RESIDENTIAL STREET Smith St, Manly	December 2001	80 mm Ecoloc	Eastern side in car parking lane	632 - 818	1754 - 2272
			In road adjacent to driveway	168	438 - 519
ROAD Terralong Street, Kiama	October 1997	80 mm Ecoloc	Roadway - SE end	113 - 145	313 - 405
			Roadway - NW end	71- 109	196-303
CAR PARK Victoria Park, Chippendale	December 1999	80 mm Eco-Trihex	High point	1080	3000
			Low point	147 - 206	408 - 571
PARKING BAYS Karrabee Avenue, Gladesville	June 2000	60 mm Eco-Trihex	Car parking along asphalt road – High point	192 - 267	533 - 741
			Car parking along asphalt road – Low point	335 - 436	930 - 1212
PEDESTRIANS + VEHICLES Sydney Sports Ground, Moore Park	November 1998	60 mm Eco-Trihex	High point	197 - 253	546 - 702
			Midpoint adjacent to trees	216 - 216	601 - 833
			Low point	112 - 150	312 - 417
LANEWAY Woodville, SA	August 1999	80 mm Ecoloc	Centre of pavement	180	500

As shown in Table 1 it was observed that often, but not invariably, the infiltration rates measured at the lowest elevations in the pavement were less than those measured at higher elevations, presumably because of sediment migration to the low points. Overall, the data given in Table 1 provide a useful check on the infiltration values needed for hydraulic design. To allow for the effects of clogging in service it is not advisable to use manufacturers' values of infiltration for pavers determined by laboratory tests because these do not reflect the effects of clogging. In some countries it is deemed sufficient for design to assume that permeable paving will achieve infiltration rates in service that are no more than 10% of the initial values measured in-situ or in the laboratory. However, a better approach is to quantify changes in the infiltration capacity of PICP over time. Experience in Europe and in-situ tests show reductions in PICP permeability due to clogging reach a near equilibrium condition between 5 and 10 years after construction (Dierkes et al., 2002; Borgwardt, 2006; Kadurupokune and Jayasuriya, 2009). The PERMPAVE program incorporates values of surface infiltration gained from in-situ tests of more than 60 permeable pavements in Germany (Borgwardt, 2006). Published equilibrium values of infiltration at 6+ years range from about 200 l/sec.ha to 900 l/sec.ha depending on the type of paver. From Table 1 it may be seen that the infiltration rates measured in Australia ranged from 312 to 3 000 l/s.ha (112 to 3000 mm/h.m^2). The average infiltration rate was about 800 l/sec.ha. i.e. slightly less than the maximum equilibrium value reported in Germany. Overall, the results demonstrated that, even for pavements that had received little routine maintenance, the infiltration rates 8 to 10 years after construction remained at serviceable levels.

Drainage Voids and Jointing Materials

As noted above, work in Europe and Canada indicates that the infiltration capacity of PICPs can largely be restored by removing and replacing the top 10 to 25 mm of the drainage material in the paving joints and openings (James 2002, James and von Langsdorff, 2003). To examine this further a study was made of the materials filling the drainage voids. For each of the pavements tested, the upper and lower 30mm of drainage material was sampled (i.e. to a total depth of 60 mm below the upper surface of the pavers). These samples were retrieved at 14 locations. The samples were dry sieved in accordance with Australian Standard AS 1289.3.6.1 to determine their particle size distributions. It was found that the drainage materials generally had a maximum particle size of 6 to 7 mm with 10% or more passing the 1.18 mm sieve and up to about 5% passing the 0.3 mm sieve size (e.g. Figure 5). This meant that the gradations typically lay towards the fine limits of the ASTM #9 grading commonly recommended in Australia both for bedding and for filling the drainage voids and joints of PICP: a specification based on laboratory testing (Shackel et al, 1996; Shackel, 1997).

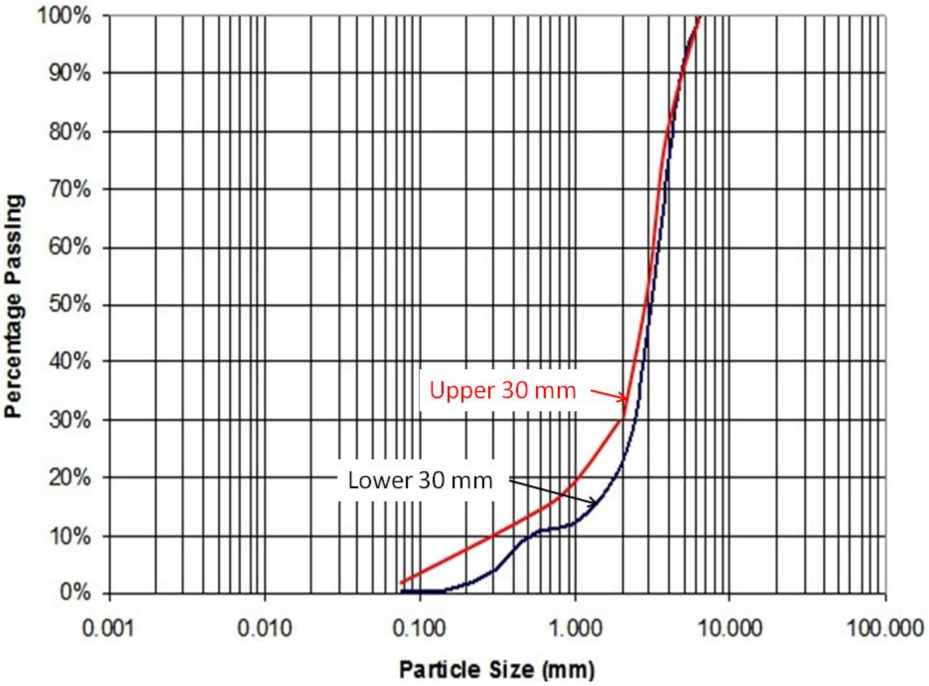

Figure 5. Typical Drainage Voids Material Grading

At 10 of the 14 locations sampled it was found that there were more fine particles in the upper 30 mm than in the lower 30 to 60 mm of jointing material. Typical results are shown in Figure 5. These indicated that the increase in fines generally occurred in the particle size range of 0.2 to 2.0 mm. The observation that most particulate material is trapped in the upper portions of the drainage openings is consistent with earlier reports from overseas (James and von Langsdorff, 2003; Borgwardt, 2006).

The drainage material sampled from areas known to have been routinely swept such as Olympic Park showed no change in fines between the upper (0 to 30 mm) and lower jointing depths (30 to 60 mm). This suggests that most of the fine clogging materials observed in the upper depths of the joint material for unswept pavements would have been located immediately at the top of the joints, i.e. from whence it could easily be removed by sweeping. To test this hypothesis further, infiltration tests were repeated on three sites after manually sweeping the surface with a stiff broom. At two of these locations the measured infiltrations were significantly greater than for the as-found surfaces (Shackel et al, 2010). Overall, the results suggest sweeping is beneficial to performance. However, as shown in Table 1, many pavements maintained satisfactory infiltration performance without maintenance. Further study of maintenance measures is therefore warranted.

SUMMARY AND CONCLUSIONS

1. Permeable pavements can make a significant contribution to sustainability consistent with the concepts of Water Sensitive Urban Design (WSUD). Overseas studies and experience have shown that this can be achieved without increase in project costs.
2. PICP systems have been studied for more than 20 years, including Australian research since the early 1990s.
3. Australian PICP research has embraced measurements of infiltration rates, structural capability, pollution trapping and clogging.
4. Australian and overseas studies have provided sufficient data to allow the design of PICP for all types of pavement to proceed with confidence.
5. This paper has detailed the development of a comprehensive methodology for the design of PICPs in the Australian context that is consistent with WSUD principles and local practice for managing rainfall runoff and water quality.
6. The methodology embraces stormwater management (flood control), water quality and water harvesting; factors rated as important by municipal engineers engaged in water sensitive urban design. The pavement must also be designed to withstand the effects of traffic. To achieve this, the new hydraulic design package, PERMPAVE has been integrated with existing structural design software, LOCKPAVE.
7. This development of the design methodology software has been complemented by field investigations of the hydraulic conductivity of permeable pavements in both New South Wales and South Australia.
8. In design, care must be exercised in the selection of the type of paver as this affects both the hydraulic and structural performance of the pavement.
9. Basecourse materials for PICP have to date received only limited study. Such studies indicate the need to use substantially reduced moduli for granular materials in structural analyses of PICP. However, ongoing studies have shown that cement treated materials may also have a role in PICP construction.
10. Because of the need to serve at high saturations, the design moduli of PICP base materials is only about 50% of the values determined by routine repeated triaxial load tests.
11. The field studies have confirmed that clogging of PICP is a natural ongoing process that must be considered in design.
12. It has been found that the majority of the sediment causing clogging is retained in the upper horizons of the material filling the drainage voids and that this sediment can be removed with sweeping. Although the testing indicated that frequent pavement sweeping may not be routinely required, further study of maintenance is needed.
13. Despite clogging over periods of 8 to 10 years, the test results showed that the pavements studied still exhibited good infiltration rates. As noted above, previous studies have shown that little change in pavement conductivity occurs after periods in service of 6 to 10 years. Accordingly, it may be concluded that, subject to the correct choice of design parameters, PICP can be expected to serve satisfactorily for periods comparable to other forms of pavement.
14. An important finding was that "as new" infiltration rates should not be used for the design of permeable pavements. Instead, a clogging factor needs to be applied in the design of PICP to allow for the incremental clogging that occurs. Further research needs to focus on quantifying these clogging factors for design purposes.

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