DESIGN OF PERMEABLE PAVING SUBJECT TO TRAFFIC

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SUMMARY

Permeable paving offers significant benefits over conventional pavements in terms of sustainability and environmental impact. Such pavements need to be designed not only to carry traffic but also to manage runoff, infiltration and pollutant transport. 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.

The concepts of permeable pavement design are outlined and the need to integrate with Water Sensitive Urban Design principles is emphasised. Progress in the characterisation and development of permeable pavement materials is described and current design data are assessed. The use of such data in the design of permeable pavements is then discussed.

1. INTRODUCTION

In urban catchments, road surfaces can account for about 20% to 25% of impermeable surfaces i.e. roads are a major generator of runoff. The control of this runoff is the prime objective in Water Sensitive Urban Design, WSUD (Argue, 2004) or its British equivalent SUDS (Pratt, 2001; Interpave, 2004). One way to achieve this is to use Permeable Interlocking Concrete Paving (PICP). PICP was first developed in Europe nearly 2 decades ago and has been used in Australia since 1997. Because water infiltration is actively encouraged a wide range of environmental benefits can be achieved (Shackel, 1996a, 1996b, 2005).

Worldwide, emerging regulations for new urban pavement developments typically include requirements for:

- On-Site retention of rainwater
- Control of the discharge rate
- Control of the discharge Water Quality
- Limits of the extent of impermeable areas
- Measures to reduce sedimentation and/or pollution

To meet such requirements in the context of Water Sensitive Urban Design, Best Management Practices (BMP) include controls for reducing or managing pollutants, procedures for the proper disposal of waste and the use of flood management procedures which assess impacts on water quality (Argue, 2004).

Permeable paving should be considered as an option when the stormwater sewerage is near or at capacity, when there are limitations on the extent of impermeable cover, when there is insufficient space for both vehicle use and detention ponds and when water quality and pollution control are primary design objectives. For these reasons, PICP provides an option in Water Sensitive Urban Design that is especially relevant to urban roads and streets (Shackel et al, 2003). However, it should be recognised that PICP has also been successfully used in heavily trafficked applications ranging up to container yards carrying industrial loads (Knapton and Cook, 2000; Anon, 2002b).

2. TECHNOLOGY

In Australia, research into PICP has been conducted at the University of New South Wales (UNSW) since 1994 and more recently has been initiated at the University of South Australia (UNISA). At UNSW the research has concentrated on laboratory studies of water infiltration through PICP (Shackel, 1996, 1997; Shackel et al, 1996), the structural capacity of permeable pavers (Shackel et al, 1996, 1997, 2000; Shackel, 2001) and the properties of base materials for permeable pavements (Shackel et al, 2001). This work has been extended to full-scale field studies with emphasis on water quality and pollution control (Shackel et al, 2003). At UNISA both laboratory and field trials have been conducted with emphasis on pollution management (Anon, 2002a; Rommel et al, 2002). The UNSW and UNISA studies show that permeable pavers can accept rainfall intensities of up to about 600 l/sec/ha whilst maintaining levels of structural capacity that are comparable with those exhibited by conventional paving. Moreover, there is good evidence that eco-paving can trap up to about 90% of particulate contaminants (Anon, 2002a; Rommel et al 2002).

Permeable Interlocking Concrete Pavement (PICP) is comprised of pavers overlying fully engineered permeable base and sub-base and the designer needs answers to the following questions:

1. What pavers and pavement materials are suitable for use in PICP?
2. How can the pavers and pavement materials be characterised for design purposes?
3. What design methodology should be used?
4. What levels of stormwater management and structural performance can be achieved?

2.1 Pavers

One of the first questions that a designer must address is the choice of paver. Pavers which allow water to infiltrate have been described in detail elsewhere (Shackel, 1996). For convenience they can be divided into the 5 categories shown in Table 1. Amongst the pavers categorised in Table 1, those utilising openings along the joints have received the most research and exhibit levels of structural capacity that are comparable with those achieved by conventional paving (Shackel 1996b, 2001, Shackel et al 1996, 1997, 2000). By comparison, as shown in Table 1, other types of permeable pavers are either untested or else are limited in their ability to accept water and/or traffic.

2.2 Bedding and Jointing Materials

Infiltration and structural tests of a wide range of permeable pavers have been reported (Shackel et al, 1996, 1997, 2001). Bedding materials ranging from ASTM C33 bedding sand to ASTM #7 (10mm) aggregates have been evaluated. It has been found that the best compromise between high water infiltration and good structural performance comes from the use of a clean 2-5 mm aggregate e.g. #9 ASTM grading (Shackel et al, 1996). This can be used for both bedding and jointing the pavers. This simplifies construction because tests and experience show that, even where the nominal joint width is

3mm, sufficient material enters the joints to ensure structural integrity.

Table 1. Suitability of Permeable Pavers for Traffic

Paver Type	Description	Structural or infiltration Test Data	Suitability to carry traffic
Paving systems with enlarged grass joints	Pavers are widely spaced using plastic or concrete spacers so that grass can grow between the pavers.	unavailable	Car parking only – No trucks or commercial vehicles
Grass stones & grids	Pavers with large openings within which grass is grown, effective in trapping pollutants but permit only small water flows. Unsuitable for sustained truck traffic.	Smith (1984) Anon (2002a)	Occasional Light Traffic
Pavers with widened joints	Pavers provided with spacer lugs which provide much wider (10mm) joints than those customarily specified for concrete segmental paving (2 to 5mm). Joints are filled with aggregate. Water flows through joints	unavailable	Light Traffic
Porous Pavers	Pavers made from porous concrete. Water flows primarily through pavers themselves	Dierkes et al (2002)	General traffic
Pavers with openings along joints	Paver openings and joints are filled with aggregate. Water flows only through openings and joints	Anon (2002a) Shackel et al (1996,1997, 2001)	General traffic

2.3 Base and Sub-Base

The base and sub-base materials for permeable eco-pavements should meet the following criteria:

1. The materials should possess adequate water storage capacity and be able to drain water within a reasonable period of time without erosion or migration of fines.
2. The materials should possess adequate stiffness to carry the full spectrum of traffic loads and repetitions.
3. The materials should be capable of trapping and removing contaminants from water draining through the pavements
4. The materials should satisfy geotechnical filter criteria which prevent movements of fines between the bedding and base, base and sub-base or base/sub-base and subgrade. Alternatively, filter fabrics can be used although there is a risk that these may become clogged over time.

Once water has infiltrated the pavers and bedding, any additional water than can be accepted by the pavement depends upon the permeability of the base and sub-base. In practice most PICP permeable pavements constructed to date have used open graded permeable base, sub-base or drainage layer materials developed by State or Municipal authorities for conventional pavements. Most commonly these comprise unbound granular materials. Many gradations have been published and both repeated loading test and permeability data are available (e.g. Applied Research Associates, 2005).

In addition to the use of conventional open graded materials, there is a need to develop new materials that combine high permeability with good structural properties. For this reason the author examined the effects of changes in the grading of a crushed rock upon both the permeability and stiffness of the materials under laboratory conditions. The material selected for study was a 20 mm crushed rock widely used for pavement construction in the Sydney region. The material was tested both as delivered and after removal of the material finer than either 0.600 mm or 1.18 mm. The gradations from which the 1.18 mm and 0.600 mm had been scalped were also tested after removal of particles bigger than 13.2 mm. Scalping out the fines led to reductions in both the modified Maximum Dry Densities (MDD) and the corresponding Optimum Moisture Contents (OMC) irrespective of the maximum particle size.

The mechanical properties of the various materials were assessed by repeated loading triaxial tests under drained conditions using specimens that were 150 mm in diameter and 300 mm high. Compaction was adjusted to achieve not less than 96% of the modified MDDs. Unlike most published studies of resilient moduli, care was taken to saturate the specimens prior to testing because PICP, in contrast to conventional CBP, must be designed to perform in saturated conditions for much of their service lives. The specimens were saturated using back-pressure techniques. Specimen conditioning and resilient modulus testing were performed in accordance with Australian Standard AS1289.6.8.1 whilst the permeabilities of the materials were obtained using a 190 mm diameter rigid wall falling head permeameter (Shackel et al, 2001).

The test gradings were characterised in terms of the Coefficient of Uniformity, C_u. As might be expected, the permeability decreased significantly with increase in C_u. In other words, the more uniform the material the greater the permeability. The materials with all fines smaller than 1.18mm scalped out exhibited permeabilities almost 100 times greater than the unmodified material. Similarly, the materials with the fines smaller than 0.600mm removed exhibited about a forty-fold increase in permeability. In this respect, the materials having a maximum particle size of 13 mm exhibited slightly smaller values of permeability at a given value of C_u than the 20 mm material.

Overall, it was clear that simple measures such as scalping out fines could greatly increase the permeability of the materials. The question remaining was the extent to which the mechanical properties might be adversely affected by such removal of fines. For convenience, the Resilient Modulus, M_r, was selected as the parameter that would best describe the mechanical properties. Values of M_r have been published elsewhere. For permeable granular base materials values of M_r ranging between about 250 MPa and 550 MPa can be assumed for materials near OMC with the range of values decreasing to between about 250 MPa and 400 MPa at high saturations > 90% (e.g. Shackel, 1973; Shackel et al, 2001). These values are stress dependent and due allowance for this must be made during structural design. This can best be achieved by using computer-based mechanistic design analyses (Shackel, 2003).

The response of the materials to repeated triaxial loading depended primarily upon the degree of saturation ruling during the test and on the particle size distribution. Irrespective of the repeated stress levels, the Resilient Modulus decreased with increase in the degree of saturation. In general, an increase in saturation led to reductions in M_r between about 40% and 70% depending on the gradation and maximum particle size.

For the materials studied, the Resilient Modulus, M_r, increased with increase in C_u. The tests showed that the permeability of a typical crushed rock base material could be increased by up to two orders of magnitude by scalping out the finer fractions of the material. This was accompanied by a reduction in M_r. Removing material smaller than 1.18mm reduced M_r by between approximately 30% and 55% whereas scalping just material smaller than 0.600mm caused modulus reductions between about 20% and 45%. In other words, the choice of unbound material for permeable base must be a compromise between high permeability and low modulus (low structural capacity).

Overall, the tests showed that it is feasible to manufacture highly permeable base materials by the simple expedient of scalping out some of the finer fractions of material. However, for design purposes it would be prudent to assume that the resilient moduli, M_r, of such scalped base materials would only be about half those normally used in mechanistic pavement analysis and design.

3. DESIGN OF PERMEABLE PAVEMENTS

Several distinct needs must be addressed in the engineering design of permeable pavements. Ideally the methodology should embrace the following objectives:

1. Flood mitigation by retention or detention i.e. water quantity.
2. Water quality improvement by filtration or retention i.e. water quality.
3. Water conservation by collection and re-use i.e. water harvesting.
4. The ability to carry traffic

The principal design questions are:

1. What is the design life of the pavement?
2. How fast can pavement accept rainfall? This depends on the paver type, the crossfall, the bedding & drainage materials and the type of base and sub-base
3. How fast will pavement drain? This is related to the type of base and sub-base, the type of subgrade and the position of water table
4. How much water can pavement retain? For how long? These questions depend on the thickness and permeability of the pavement layers.
5. How thick should the pavement be to carry traffic? Here the resilient properties of permeable pavement materials are paramount.

3.1 Design Life

A major advantage of PICP is that it can trap around 90% of TSS pollutants i.e. particulates. Research shows that gradually over time these particulates accumulate in the pavement and that consequently the pavement slowly clogs. Experimental work at UNISA has established that effective lives between 15 and 25 years are feasible (Anon, 2002a). Moreover, it has been shown that much of the clogging occurs in the jointing materials from whence it can be easily and economically removed (James, 2002; Dierkes et al, 2002; Shackel, 2005). Based on these studies it appears reasonable to adopt a 20 year maximum design life for PICP. To address the remaining questions requires the selection of the cross-section, stormwater management and structural design.

3.2 Cross-section Selection

The first step in PICP design is to determine how the water will be controlled and managed within the pavement system i.e. to choose a cross-section and the pavement materials. Broadly three cases need to be considered:

1. Where the water infiltrating the PICP is allowed to flow into the subgrade and thence to the water table. Here subsurface drains may sometimes be omitted. Some local authorities will not permit this and it is only feasible on permeable sandy soils.

2. Where the PICP is founded on an impermeable clay subgrade provision must be made to drain the water from the site using drainage pipe and a filter fabric must be used to prevent clay fines contaminating the base and sub-base.
3. Where there are contaminated flows, issues of soil salinity or the subgrade soil is expansive. Here an impermeable liner needs to be placed between the PICP and the subgrade and drainage pipes are required to remove infiltration.

Suitable cross-sections for achieving these objectives are available (e.g. Smith, 2006; INTERPAVE, 2005).

3.3 Water Infiltration and Treatment

Three issues must be considered in the design of pavements to handle water. These are:

1. *Stormwater Management* i.e. how much water can the pavement infiltrate over a given time and where will it go?
2. *Pollution Control* i.e. what will be the quality of the effluent leaving the pavement?
3. *Water Harvesting.* To what extent *i*s it possible to store and reuse the water?

3.3.1 Stormwater Management

To design PICP for water management several general methods using nomographs have been published (e.g. Smith, 2006; INTERPAVE, 2005) and software based on the USEPA stormwater management program, SWMM, exists for one proprietary permeable paver (James and von Langsdorff, 2003). However, pollution control and water reuse also need to be considered to achieve an effective outcome in terms of the concepts of Water Sensitive Urban Design (Argue, 2004). This is best achieved by specially written software which will handle the various generic types of paver classified in Table 1. The author is currently working on the development of such programs. Before commencing this work a survey of local government engineers showed that, to be adopted, the software would need to address a number of issues in stormwater management.

Hitherto most analyses of permeable pavements have concentrated on analysing retention and/or detention of stormwater within the boundaries of the PICP site. However, detention must be integrated with overall Catchment Management in terms of runoff and water quality i.e. PICP should not be considered as stand-alone projects. Catchment management involves consideration of the catchment as a whole. Catchments may be large e.g. an entire suburb and PICPs are just elements within the catchment. The critical locations at which local authorities mandate flows and/or water quality are normally some distance away from the PICP. Therefore, the critical factor is how the PICP impacts upon the entire catchment not just its immediate locality i.e. downstream effects must be considered. This means that stormwater management software must calculate retention and detention, predict outflows and/or drainage times (emptying) and also integrate as a node in existing catchment management procedures and software. Similarly, if municipal engineers are to adopt it, the software must be capable of integrating with water quality software programs.

To date most stormwater management methods for PICP have used the Design Storm Method based on historical rainfall records. Arbitrary assumptions about the state of storage in the pavement e.g. empty or half-full at commencement of design storm must be made. The alternative is to use the Modified Design Storm Method which considers drainage (emptying) time, emptying by either infiltration/percolation or hydraulic abstraction e.g. drainage pipes. In Australia, design will soon move to continuous simulation of rainfall rather than a nominated design storm (Argue, 2004). The following inputs need to be considered for the pavement:

- Effective area 'connected' to the permeable paving system
- Proposed area of the permeable paving system
- Impervious area not draining to the permeable paving
- Pervious area not draining to the permeable paving
- Permeable paving storage
- Storage media porosity
- Soil saturated hydraulic conductivity
- Infiltration clogging
- Drainage outlet discharge characteristics

Storm data include:

- Average Recurrence Interval (ARI)
- Critical storm duration(s)
- Temporal zone
- Average storm intensity
- Antecedent condition (e.g. part-full with stormwater?)

3.3.2 Water Quality and Harvesting

Two approaches to controlling water quality can be identified. The first of these is to filter the stormwater and then release it to the local government drainage system. The second is filter and retain the stormwater on-site, allowing it either to slowly percolate to the underlying soil or to be stored in underground tanks. Factors that must be considered include:

- Input pollutant concentration characteristics
- Pollutant removal efficiency characteristics
- Historical rainfall data
- 'First flush' pollutant characteristics
- Build up / wash off of pollutants

For water harvesting (reuse) the main consideration is the monthly demand characteristics.

3.3.3 Structural Design

The pavement thicknesses required for stormwater management will normally be different from those needed to carry traffic. This means, that in addition to water management, it is necessary to consider the structural design of the pavement. PICP has already been successfully used in projects ranging from car parks to roads, ports and container yards. Accordingly, any structural design procedure should be capable of handling both a wide range of loading conditions and the full range of new materials needed for the construction of PICP. Mechanistic pavement design software for achieving this already exists. For example, the LOCKPAVE software, in use in the USA, Canada and many other countries around the world, can model permeable pavers and permeable base and sub-base materials (Shackel, 2000). In this program resilient modulus data such as those summarised above for base materials can be used for the design of PICP and many different types of paver can be considered. This mechanistic methodology therefore is complementary to the water management methods that already exist or which are in development.

One problem facing the designer of PICP is to choose the moisture content at which the base and sub-base materials must serve because this affects the stiffness, M_r, of the materials. As noted above, M_r falls with increase in saturation yet most studies of M_r have been reported for relatively dry conditions close to OMC. General relationships between M_r and moisture content for base and sub-base published in Australia (AUSTROADS, 2004) show that, at high moisture contents, M_r values may be only 50% or 60% of those customarily used in mechanistic pavement design for materials meeting current base or drainage layer specifications. As noted earlier, similar reductions in M_r are appropriate when using scalped granular base materials (Shackel et al, 2001). In the absence of M_r values that have been measured at high saturations it is prudent for the designer to choose M_r values that are typically only about half those routinely adopted.

The use of lower M_r values than are commonly selected for the structural design of conventional pavements will lead to some increase in base or sub-base thicknesses for PICP compared to CBP. However, as noted above, the final design thickness for a PICP is the greater of the thicknesses need for stormwater management and for carrying traffic. In the author's experience the thickness needed for water management is often greater than that needed for traffic. This means that there is usually no economic disadvantage in requiring greater structural thicknesses for PICP than for conventional CBP because stormwater considerations often determine the final design. However, it would be unwise to assume that this will always be the case, especially where heavy traffic must be carried. Accordingly, the stormwater design should always be accompanied by a structural analysis.

4. CONCLUDING COMMENTS

Worldwide, the use of PICP is increasing rapidly with applications ranging from car parks to container yards (Shackel, 2005). Testing of PICP systems and materials has now been going on for more than 15 years. In Australia alone, more than 7 different systems have been evaluated ranging from grass block to pavers. Much of this research has concentrated on the pavers and their bedding and jointing materials and extensive information is available on both the hydraulic and structural properties of the paver and bedding courses. There is also good information available on the ability of PICP to trap pollutants and on the clogging that accompanies this process (Shackel, 2005). Allowing for clogging and its remediation, it appears reasonable to adopt design lives of up to about 20 years i.e. similar to those used for conventional CBP.

Overall, there is now sufficient data to allow the design of PICP for all types of application to proceed with confidence but, especially in the area of stormwater mitigation, the existing methods tend only to address site-specific water management and do not integrate with the catchment management procedures and water quality software now in routine use by municipal engineers. Overall the stormwater design must calculate or nominate retention and detention as required, predict outflows to the surrounding catchment, integrate as a node in existing catchment management procedures and software and be compatible with water quality monitoring programs. All these factors are rated as very important by municipal engineers for whom water sensitive urban design is a basic requirement. If PICP is to reach its full potential it will be necessary for new design software to be developed which embraces stormwater management, water quality and water harvesting. Such software must integrate or co-exist with existing catchment management and water quality software. Organisations such as the Concrete Masonry Association of Australia are meeting this challenge and new PICP design software is about to be released.

Structural design software is already available for the mechanistic design of PICP for both roads and heavy duty port and industrial paving. As noted above there are good data on the structural performance of permeable paving so that realistic inputs for paver modulus can be used. However, the data on permeable base and sub-base materials are less extensive and more research is needed in this area. Caution needs to be shown in choosing moduli to characterise granular permeable base and sub-base materials. At the high levels of saturation expected for PICP in service it is prudent to adopt much lower resilient modulus values than have been used hitherto in the design of conventional CBP. Accordingly, to carry traffic, PICP will often be thicker than conventional CBP. However, this is of minor concern because experience shows that greater pavement thicknesses are often required for stormwater management than for carrying loads and traffic.

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