DEVELOPMENT OF DESIGN SOFTWARE FOR PERMEABLE INTERLOCKING CONCRETE PAVEMENTS

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Note: The following is the notation used in this paper: (.) for decimals and (   ) for thousands.

Summary

This paper describes the development of new design software for Permeable Interlocking Concrete Pavements (PICP). The software was first developed for Australian conditions but has subsequently been extended to other countries. The software is unique in that it permits permeable pavements to be designed to satisfy the requirements of stormwater management and flood control, to control the quality of water leaving the pavement and, where required, to permit water to be stored and harvested for later re-use. In addition, the program is designed to interact with structural design software so that permeable pavements can be designed for a wide range of traffic conditions including car parks, roads and streets and industrial pavements carrying heavy off-road vehicles.

The structure of the program is described and it is shown that a sequential stepwise process is the most logical design approach. The technical justification for each of the design steps is provided based on research published both in Australia and overseas. The program has been developed to be consistent with the principles of water sensitive urban design. Details of the methodologies used for flood management, the control of water quality and for water harvesting are described and the requirements for adapting these to suit different countries and regions are then discussed. Finally, the role of vehicular traffic in the design process is described.

1. INTRODUCTION

Permeable pavements offer an economical and sustainable way of developing and enhancing urban infrastructure. In Australia, research into the structural and hydraulic properties of permeable paving has been conducted for about 15 years. The outcomes of this research are being increasingly utilised as best management practice where municipal authorities commonly face the following problems:

1. Rapidly expanding urban development requiring the deployment of new and expensive drainage infrastructure.
2. Urban Consolidation which concentrates and increases development within existing city boundaries. This imposes increasing and often unsustainable demands on existing urban drainage infrastructure.
3. Increased urban runoff leading to flooding and erosion.
4. Runoff leading to pollution of rivers, streams and wetlands.
5. Increased demands for water use.

PICP can address all the municipal runoff problems listed above. Moreover, permeable pavements not only embrace stormwater management and pollution control but yield significant economic advantages by minimising the costs of surface drainage works, reducing the demands on stormwater sewerage and optimising land use [Shackel, 1997, 2005; Shackel at al, 1996; Shackel and Pearson,1996; Interpave, 2006].

In Australia, stormwater runoff is addressed under the principles of Water Sensitive Urban Design, WSUD, known as low impact development in the UK. This aims to manage stormwater and pollution at either the site level or on a regional basis [Argue, 2004]. WSUD is referenced by planning guidelines and drainage regulations and provides a rational framework for managing urban runoff. Permeable paving provides a Best Management Practice (BMP) by providing measures for:

- Managing surface runoff.
- Retaining or detaining water so as to control the flow into stormwater drains and sewers.
- Removing pollutants at source.
- Harvesting and storing water for reuse.

To be consistent with WSUD any formalised procedure for designing permeable pavements must address each of the issues listed above. This paper now describes the development of such a design tool for PICP.

2. OVERVIEW OF PERMEABLE PAVEMENT DESIGN

For PICP the factors that need to be considered in design are shown in Figure 1. Although some PICP design methods allow a designer to consider these factors in any order, a review of the literature of PICP shows this to be illogical because decisions that have to be made at the various stages of design are often dependent on the values of factors chosen elsewhere. For this reason the authors have developed the sequential stepwise design process shown schematically in Figures 1 and 2.

The sequence and significance of each of the factors shown in Figure 1 is now briefly discussed.

1. **Purpose of the Pavement.** The first design question that needs to be resolved is the purpose of the design i.e. whether the design is for managing stormwater runoff flood control, water quality improvement or for harvesting and reusing water. The reason for beginning the design process here is that the rainfall data and modelling is different for each of these objectives. As discussed below, the choice of design storm and the modelling of rainfall for stormwater management is quite different from that needed for water harvesting. Furthermore the magnitude of rainfall intensity selected for design may influence the type of paver that should be selected in order to cope with the runoff flows.

2. **Type of Application.** PICP has been successfully used for a wide variety of applications ranging from hard landscaping to car parks, streets and container yards. The type and amount of traffic needs to be considered both to determine whether a structural analysis is required in addition to a hydraulic analysis and to ensure that a suitable paver is selected to resist traffic loads.

3. **Subgrade Conditions and Choice of Cross-section.** The subgrade soil determines the type of pavement cross-section that may be feasible (see Figure 2). Where the subgrade is a granular sandy or gravelly material it may be possible to fully infiltrate all of 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 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 temporarily to detain the water and then to allow it to efflux via a carefully sized outlet to the stormwater drains 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.

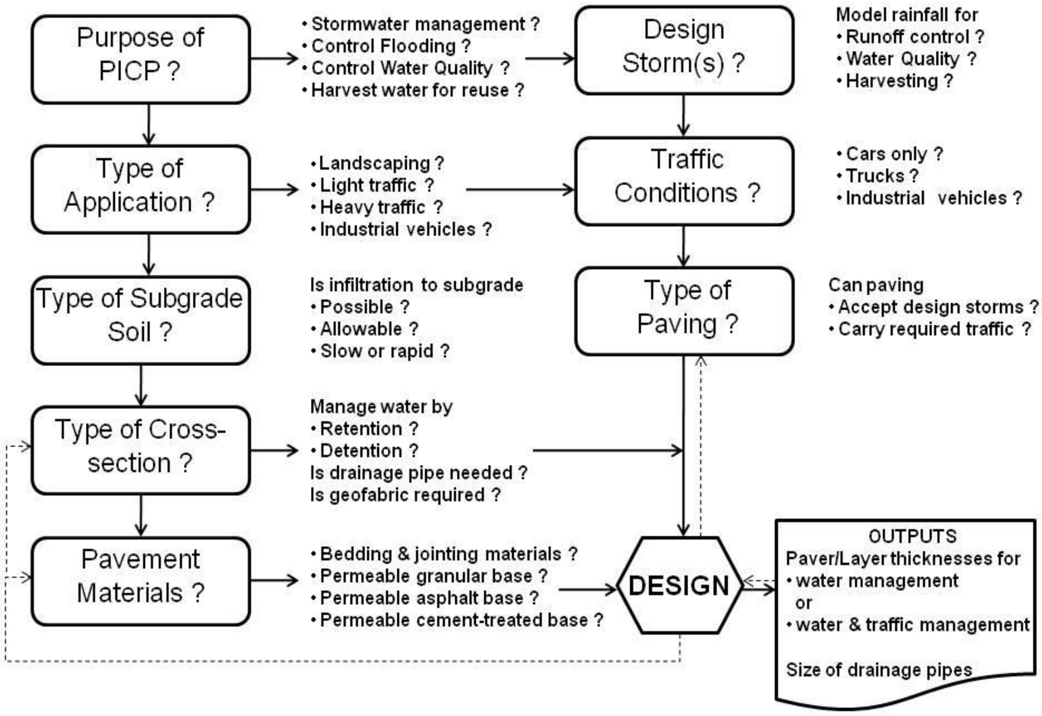

Figure 1. Principal Design Factors and Design Questions.

4. **Paver Type**. When first installed almost all types of permeable paving can accept very high rainfalls which are usually substantially in excess of any value likely to be chosen for design. However, both laboratory tests and field measurements of PICP have shown that, as the pavements retain pollutants, they gradually clog until, within 6 to 10 years after construction, the rate at which they can infiltrate water is significantly less than the initial values, [e.g. UniSA, 2002; Borgwardt, 1997, 2006; Beecham et al, 2009]. At this stage, not all types of permeable paver exhibit equal infiltration rates and allowance for this must be made during design. Moreover, not all permeable pavers perform equally under traffic loads [Shackel et al., 2000] and this needs to be considered in pavement design.

5. **Pavement materials**. The basecourses most commonly used in PICP comprise unbound granular materials but permeable asphalt, permeable concrete or cement stabilized materials can also be used successfully [e.g. Zhuge and Hazell, 2007; Oeser et al., 2009]. Here the main input required for design is the voids ratio because this determines the amount of water that that be stored in the base. Where the pavement is to carry traffic it is also necessary to know the Resilient Modulus of the saturated base material so that a structural analysis can be made [Shackel at al, 2001].

Once all the inputs have been considered in the correct sequence (see Figure 1) it is possible to design the pavement following the paths shown schematically in Figure 2. This gives the thicknesses required to manage water infiltration, the size of drainage outlets, and, where necessary, the thicknesses needed to resist traffic loads

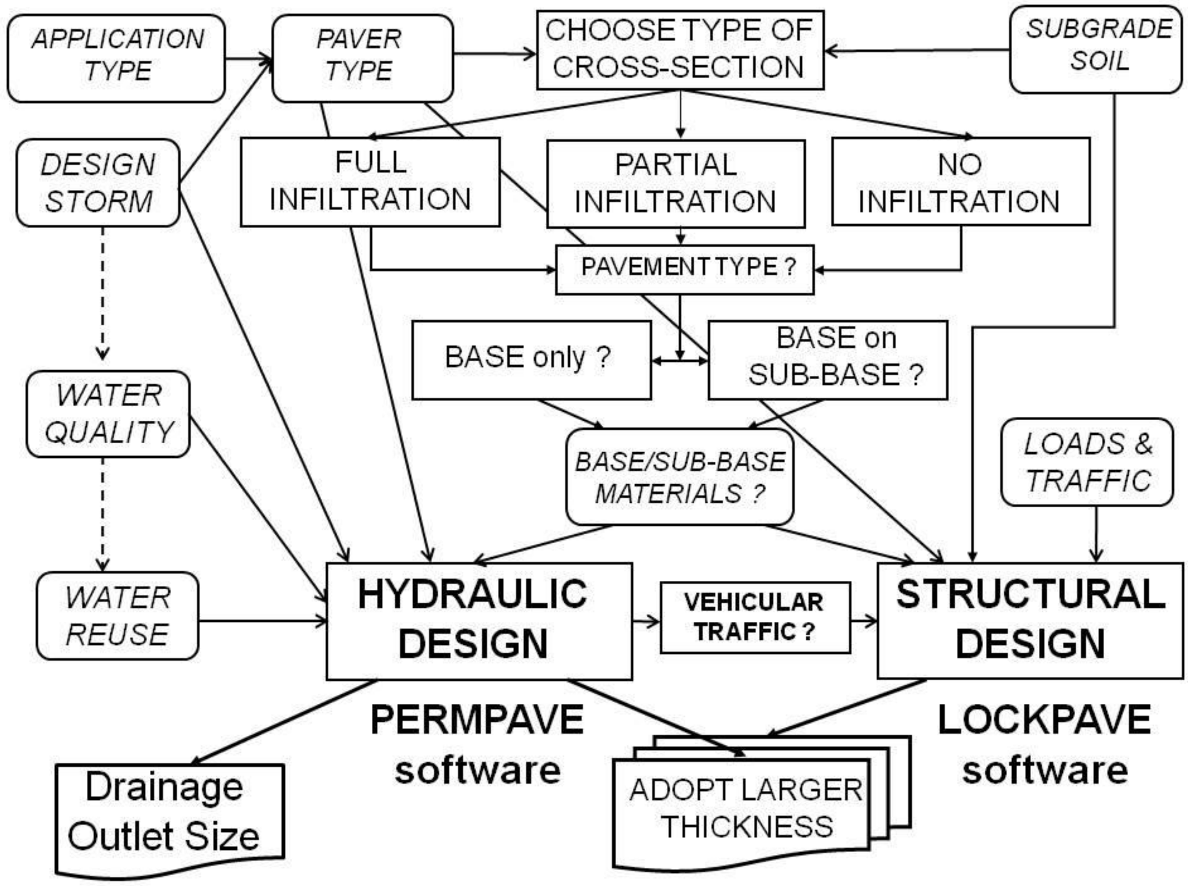

Figure 2. Schematic of the Design Process.

3. PICP DESIGN

From Figure 2 it may be seen that there are two major components in the design process. These are a hydraulic analysis for managing water supplemented, where vehicles must be carried, by a structural analysis. Usually the thickness needed for water management will be different from that required to carry traffic and the greater of the two thicknesses will need to be adopted (Figure 2). Thicknesses are normally calculated iteratively and, as shown schematically by broken lines in Figure 1, a designer will need iteratively to try different materials, types of paver or cross-sections. Because of the iterative nature of PICP design it is best implemented by means of software. The software developed for water management is known as PERMPAVE. This is linked to the LOCKPAVE structural design program used both in Australia and around the world for many years [Shackel, 2000]. Unlike earlier PICP programs such as PC-SWMM [James and von Langsdorff, 2003] these programs do not simply analyse some structure nominated by the designer but, rather, iteratively calculate the thicknesses need to satisfy the design inputs and requirements.

The LOCKPAVE software is well known and has been extensively documented [e.g. Shackel, 2000]. Accordingly, further discussion here is limited to the PERMPAVE program. The most important elements of this program comprise:

1. *Flood control* to calculate the capacity the pavement to manage design rainfall events by infiltration to the subgrade or to the storm sewers
2. *Pollution Control* to determine the quality of the effluent leaving the pavement.
3. *Water Harvesting* to determine the extent to which is it possible to store and reuse the water.
4. *Integrating The Design Of Drainage Outlets* with the pavement design.

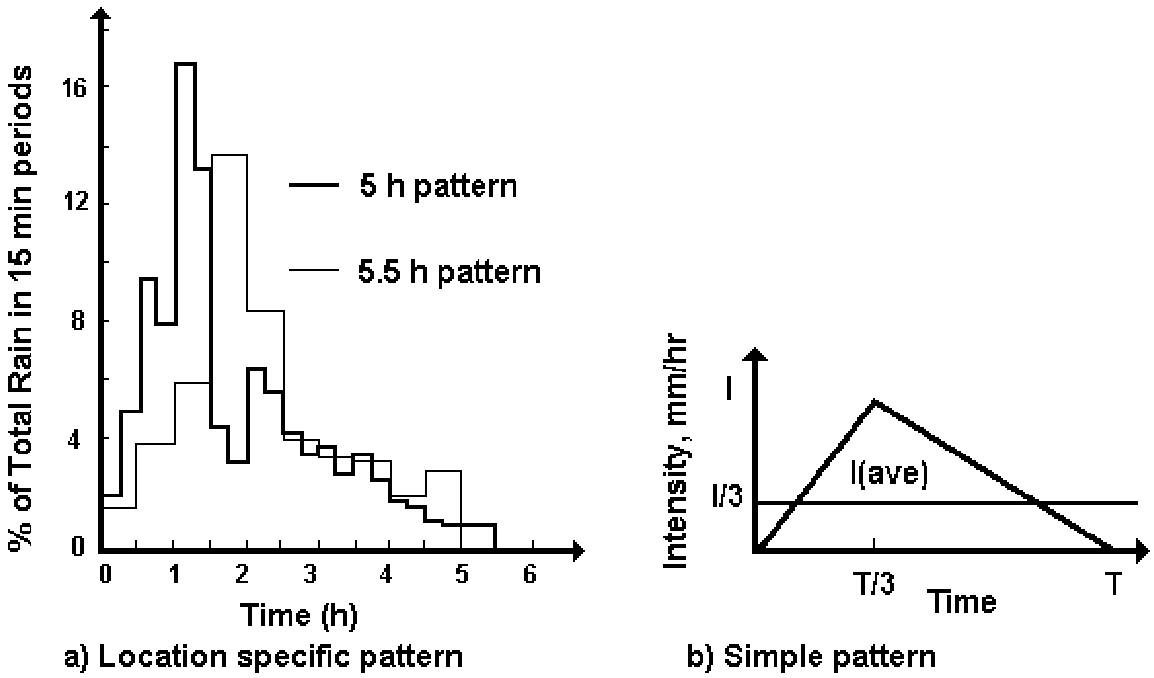

Figure 3. Storm temporal patterns applied to design average storm intensity.

4. FLOOD CONTROL

The PERMPAVE program uses the design storm approach as commonly specified by local municipalities using simple methods derived from continuous modelling that can be incorporated into standard design procedures [Engineers Australia, 1999 and Argue and Pezzaniti, 2005]. 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 can be applied to the average storm intensity to provide a rainfall distribution pattern over a period of time (e.g. Figure 3a). Where storm temporal patterns have not been developed a simplified triangular pattern is applied, as shown in Figure 3b. The rainfall temporal pattern is generally peculiar to specific geographic zone or region. Design inputs include the effective area connected to the permeable paving system, the area of the permeable paving system, hydraulic conductivity of the paver block layer, any impervious area draining to the permeable paving, the permeable paving storage, the saturated hydraulic conductivity of the subgrade and the drainage outlet discharge characteristics.

Storm data include the Average Recurrence Interval (ARI), the critical storm duration(s), the temporal zone, the average storm intensity and antecedent condition (e.g. is pavement part-full with stormwater?)

A key function of the flood control module is the determination of the storage required to achieve a 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 equivalent runoff coefficient. The peak discharge assessment also considers any surface flows that cannot be managed by the pavement whether it is due to the limiting capacity of the paver layer or pavement storage volume. The design analysis considers a combined peak flow which includes both the surface and subsurface discharge flows as shown in Figure 4.

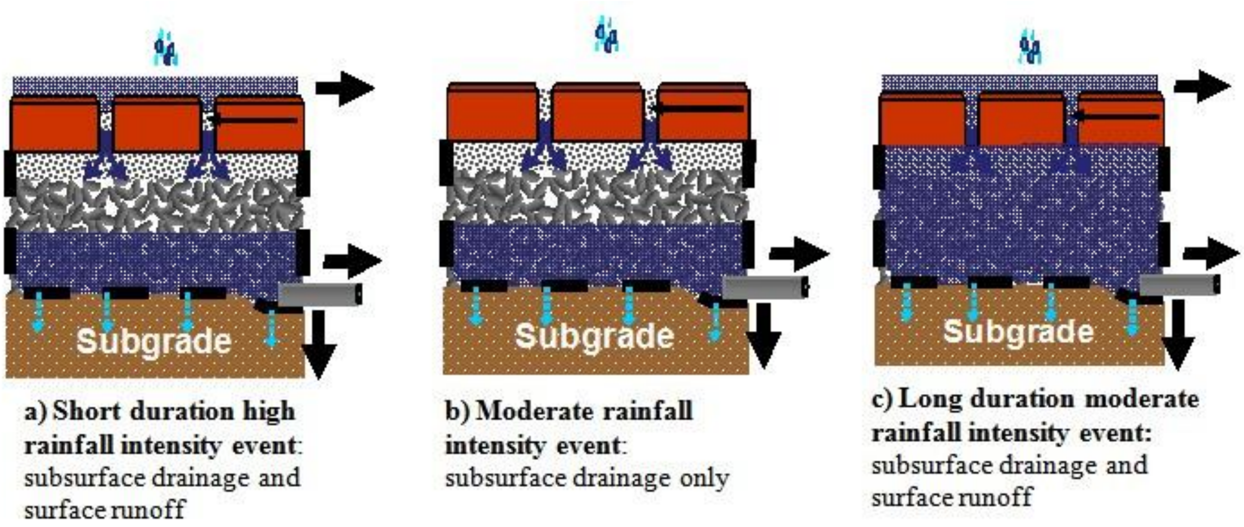

Figure 4. Flood storage and combined maximum discharge analysis modes.

When selecting the option that includes a pipe discharge with or without infiltration to subgrade, the flood module 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 is set by the program and should not be increased or reduced. Increasing or decreasing the pipe diameter size in most cases will elevated the combined peak discharge flow rate, exceeding the permitted flow rate set by the user. It is probable that the pipe diameter specified by the program will not be readily available from a supplier and in this case a large diameter pipe should be selected incorporating an orifice plate with the correct diameter.

5. WATER QUALITY AND WATER HARVESTING ANALYSIS USING HYDROLOGICAL EFFECTIVENESS

Many water quality and quantity models require intense and sophisticated modelling techniques [USEPA 2007]. When assessing systems such as permeable pavements it is important to model their performance at small time step intervals so you can consider the effect the variability of rainfall event over small periods. In many cases large volumes of data are necessary to produce realistic outcomes. In addition the effort required by an experience user can be time consuming and there is a greater potential for user input error. A key feature of the PERMPAVE program is the ability to perform difficult analysis in an efficient manner.

Water quality and harvesting/reuse analysis is undertaken using a simplified approach. A novel technique was incorporated into the software which utilized key hydrological characteristics specific to the geographical location (e.g. major cities) selected for the analysis. The technique involved the development 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 a 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 min interval rainfall data were used to generate the hydrological effectiveness relationships. For small catchments a small time step (6min) simulation is necessary to achieve reliable performance information. The key input inputs required to develop the relationships are:

- Effective impervious area (catchment).
- Historical rainfall data (10 to 20 years).
- Discharge rate (infiltration or pipe drainage).
- Storage volume.
- Average annual rainfall.

In order to produce the hydrological effectiveness relationships several important assumptions were made, being, constant discharge rate, unlimited inlet flow capacity, zero initial loss and zero evaporation loss. Although the relationship is a simplistic representation of the processes that take place key the technique produces reliable results.

The program allows the user to adjust the average annual rainfall should it be different the default value. However, it is acknowledged that rainfall variability may be significant even in small geographical locations and hence the user use caution when adjusting the average annual rainfall.

5.1 Water Quality

The water quality module uses the hydrological effectiveness relationships to assess the water quality improvement provided by the pavement. 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 load (e.g. kg/yr).

The water quality module requires the user to enter inflow concentrations (default values are provided) and removal rates, expressed as a fraction of inflow concentrations. An additional input is the target reduction in load, expressed as a percentage. The program then determines the minimum volume required to achieve the target reduction.

Where there is a discharge pipe the user will need to enter 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 not treated. For installations with both infiltration and pipe discharge only the proportion of pipe flow is treated

5.2 Water Harvesting

Like with water quality, water harvesting module utilizing similar analysis techniques. The objective of this analysis is to determine the storage volume require to meet a water demand. Three key inputs are for the analysis and they include a constant daily demand rate (l/day), average annual rainfall, and storage voids ratio.

Determining the size of storage can be subjective and although supply for a demand can be achieved it may not be necessarily to most appropriate or economical solution. In many climatic zones where there are long dry spells between rainfall events it may not be possible to meet demand in a given year, regardless of the available storage. In tropical high rainfall locations where long dry spells occur it may be possible to meet demand with large storages. Climates where there is moderate to high 'consistent' rainfall short dry spell characteristics generally result in the small storages for an equivalent demand.

With most storage systems there is a point where the return (supply) for a unit increase 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 diminishing rate of return and the other based on achieving the total demand. In addition, a graph is provided to show the relationship between storage and supply.

In order to incorporate this analysis technique two key several assumptions were adopted: zero evaporation and constant demand. Caution should be exercised particularly where constant demand (weekly) is not exhibited.

5.3 Combining the Harvesting, Water Quality and Flood Control Requirements.

Permeable pavement systems are one of few the technologies that are capable of meeting multiple water management objectives. As previously mentioned the PERMPAVE program operates in 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 function each of the relevant modules should be used separately.

In cases where flood management and water quality improvement are the two chosen functions, the module that produces the solution that requires the largest storage volume will need to be adopted. If the primary functions of the paving are flood management with pipe discharge and water harvesting the final design storage volume should be the sum of the volumes required for both functions. The reason for this is the uncertainty surrounding the available storage prior to the onset of a design storm event. It is possible the storage required for harvesting will be 'full' prior to a flood event and hence the need to ensure that an additional storage for flood management is available.

6. DESIGN FOR TRAFFIC

Where the paving is to carry traffic it is necessary to check that the thickness chosen for water management is adequate to carry the traffic loads. This can be done by running the LOCKPAVE structural design program which form part of the overall modular design process illustrated in Figure 2. As shown in this figure, LOCKPAVE should be run after completing the hydraulic design. This is because structural design only becomes an issue when the pavement is to carry trucks or other heavy vehicles. For landscaping, domestic paving and for car only parking there is normally no need for a structural analysis but parking areas open to trucks, roads, streets and industrial pavements will all need to be analyzed for traffic loads. The structural and hydraulic analyses often give different design thicknesses. Clearly the greater of these should be adopted as the final design.

7. CONCLUDING COMMENTS

PICP systems have been studied for more than 20 years. Research has embraced measurements of infiltration rates, structural capability, pollution trapping and clogging. There is now sufficient data to allow the design of PICP for all types of municipal application to proceed with confidence. For PICP the design engineer needs to nominate retention and detention as required, predict outflows to the surrounding catchment, integrate the project as a node in existing catchment management procedures and be compatible with water quality monitoring programs. . Subject to the principles outlined above, all these design processes can be facilitated by software packages such as PERMPAVE based on detailed local rainfall records. Such software is intended to help PICP is to reach its full potential by embracing stormwater management (flood control), water quality and water harvesting, factors rated as important by municipal engineers engaged in water sensitive urban design.

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