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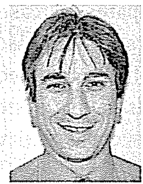

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Influence of clogging on the effective life of permeable pavements

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This paper investigates the 'effective life' (or useful lifespan) of permeable pavement installations subject to sediment loadings. The broad aims of this study, which included both laboratory and field work components, were to improve understanding of the long-term pavement hydraulic conductivity, to assess the effective life of permeable pavements and to quantify the degree of sediment trapping and associated pollutant retention. Three types of permeable pavement were investigated. For each type the effects of pavement cleaning were also investigated. Over a simulated 35 years of sediment loading conducted in the laboratory, the results showed reductions of 59–75% in hydraulic conductivity with an average sediment retention of 94%. Suspended sediment concentrations measured at the outflow of the laboratory test beds did not show any significant difference between pavers that were subjected to cleaning and those that were not. For the field studies presented in this paper, hydraulic conductivities were very high in locations where permeable pavements are subjected to small to moderate sediment loads. At other locations with high coarse sediment and organic sediment loads, hydraulic conductivity tests indicated that clogging occurred at a rapid rate, particularly where runoff flowing onto the pavement was concentrated.

1. INTRODUCTION

The guiding principles of water sensitive[1] urban design (WSUD) are centred on mitigating the adverse effects of urban stormwater runoff and achieving integrated water cycle management solutions for new urban areas released for development and urban renewal developments linked to

(*a*) reducing potable water demand through water-efficient appliances, rainwater and grey water reuse
(*b*) minimising wastewater generation and treatment of wastewater to a standard suitable for effluent reuse opportunities and/or release to receiving waters
(*c*) treating urban stormwater to meet water quality objectives for reuse and/or discharge to surface waters
(*d*) using stormwater in the urban landscape to maximise the visual and recreational amenity of developments.

WSUD is analogous to the UK sustainable drainage systems (Suds). Both WSUD and Suds embrace the concept of integrated land and water management and, in particular, integrated urban water cycle management. This includes the harvesting and/or treatment of stormwater and wastewater to supplement (normally non-potable) water supplies.[1]

In WSUD, permeable pavements are commonly used as a component of a treatment train and as a source control measure capable of reducing stormwater flows and pollution loads. Source control of stormwater, in which the runoff infiltrates and pollutants are retained, is generally regarded as the most effective strategy for achieving the long-term goals of stormwater management. Urban stormwater runoff contains significant concentrations of suspended sediment (SS) and gross pollutants. As such, there is a perception that permeable pavements used as source control devices and designed to infiltrate runoff will tend to block quickly and result in high maintenance and replacement costs. Source control measures, including permeable pavements, are most suited for use in developed areas. This is because runoff from fully developed catchments is likely to contain lower levels of sediment loading due to reduced construction activity.

Conventional pavements designed for use by vehicular traffic typically consist of a sub-grade, one or more overlying courses of compacted pavement material and a surface seal. An integral aspect of conventional pavement design involves preventing entry of water to the pavement by way of the seal to protect the integrity of the underlying base course, sub-base and sub-grade.

Conversely, permeable pavements have quite different objectives and design requirements to conventional pavements. The joints between surface pavers are not sand-filled and are designed to infiltrate stormwater through to the underlying layers. Water passes to the open graded single-sized gravel substructure and is drained through the sub-grade. The pavements therefore perform the dual function of supporting traffic loads and draining stormwater. Pollutants in the stormwater also infiltrate the pavement, with the majority being trapped within the pavement layers (Figure 1).

Little is known about the effective lives of permeable pavement systems in Australian practice because of their relatively recent emergence. Pavement effective life refers to the number of years in service before hydraulic performance has dropped to an unacceptable level. At this point, the pavement would be regarded as having failed and pavement replacement is thus

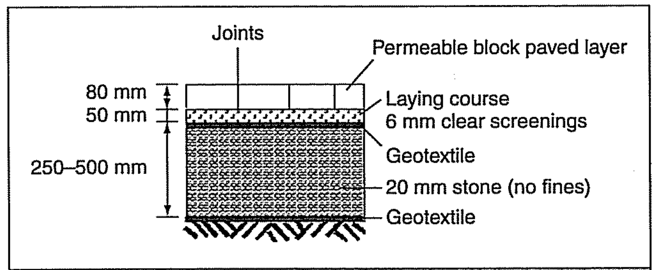

Figure 1. Typical permeable pavement arrangement (cross-section view); the joints between pavers are typically 2–3 mm wide

required. Some manufacturers claim an effective life of 20–25 years for these systems, but this is not confirmed by substantive field trial data.

Permeable paving constructed with gravel chips with 2–5 mm drainage openings was shown to have a permeability of $3{\cdot}6 \times 10^4$ mm/h as-laid, decreasing over time.[2] After 5 years, a permeability of $3{\cdot}6 \times 10^3$ mm/h was measured.

Pratt *et al.*[3] conducted a field study on four reservoirs in Nottingham, UK. The reservoirs were overlain with permeable concrete block paving and with different sub-base stone types. After monitoring discharges for water quantity and quality, it was reported that outflow water quality parameters – particularly concentrations of SS and lead (Pb) – were low in value. Pollutant outflow concentrations were significantly lower than runoff from traditional impermeable surfaces. The effective trapping of sediments in the upper layers of the pavement minimised the throughput of pollutants. It was estimated that this process could continue for 15–20 years before pavement replacement works would be required. Permeable pavements can provide some or all of the benefits of flow-attenuation, aquifer-recharge, pollution control and treatment, stored water reuse, and effluent quality enhancement for two or more decades.[4]

In a field and laboratory study, Berry[5] found that even a small percentage of infilling with sediment (2–3%) of voids within the infiltration inlet zone appeared to have a dramatic impact on the rate of infiltration. Although the storage potential of the bedding material below the surface blocks remained high, the infiltration rate was influenced by the degree of void infilling in the top 50 mm of the infiltration inlet.

Suarman *et al.*[6] studied four potential substructures for permeable paving or permeable car park surfaces over a period of 24 simulated years. The laboratory simulation used a sediment concentration inflow of 80 mg/l, believed to be comparable to values that could be expected in substructures beneath permeable paving or permeable surfaced car parks in stable and fully established suburbs. It was assumed that failure occurred when the hydraulic conductivity of the primary filter systems (in the upper 50 mm of the substructure) fell to one third of the as-constructed value. The study found that the time to failure was 25 years (or longer) of simulation for all four beds investigated.

A field study[7] on the infiltration capacity of permeable paving showed that the permeability of the pore system of the filling comprising drainage paths increases with the use of coarser mixes and that infiltration decreases with age. After five years, the infiltration was observed to decrease by 50%. A comparison of various paving systems showed that the highest infiltration performance was achieved using paving systems with drainage holes. After 6 years, infiltration reduced to around 1 mm/h.

The substructure of permeable paving was studied in a 30-year simulation of sediment loading by way of accelerated loading techniques.[8] With a sediment load of 200 mg/l, four different substructures were tested – two Grasspave and two Formpave substructures. After a simulation period of 5 years, the hydraulic conductivity dropped to 10% of its initial value. The hydraulic conductivity decreased before reaching equilibrium after 20 years for three of the four models; the equilibrium value was approximately 2% of the as-constructed hydraulic conductivity value. For the substructure comprising 5 mm rock screenings and 20 mm crushed rock, the reduction in conductivity reached an equilibrium after 40 years equal to approximately 8% of its as-constructed value.

Dierkes *et al.*[9] noted that wind-borne sediment can lead to clogging of permeable pavement systems and explained the importance of pre-filtering runoff in areas prone to the build-up of fine sediment. The pollution retention capability of permeable pavements is known and sediment control for protecting the effective life of permeable pavements is important.[10] Porous concrete can be used to improve water quality in stormwater runoff.[11]

These studies show the viability of permeable paved systems based on laboratory measurements and qualitative field experience. The broad aims of this work were to undertake laboratory studies to improve understanding of long-term changes in pavement hydraulic conductivity, to assess the effective life of permeable pavements, to test the effect of pavement cleaning and to quantify the degree of sediment trapping and associated pollutant retention. Field studies were undertaken to confirm the results obtained in the laboratory.

2. STUDY METHODOLOGY

2.1. Laboratory studies

Two specific aims identified for this part of the study were to determine

(*a*) the 'effective life' of permeable pavements by observing changes in hydraulic conductivity resulting from sediment loading
(*b*) water quality improvement in stormwater runoff by measuring SS in both the inflow and outflow.

A purpose-built test rig (Figure 2) was used to simulate 35 years of stormwater and associated SS loadings to four permeable pavement test beds. Declining hydraulic conductivities over this period were measured, leading to an assessment of effective life. The test rig supplied water of a known and measured quantity and quality to each of the four pavement beds. The rig comprised a large mixing tank and a pump that supplied input water to a distribution cylinder. This cylinder contained a second mixer to ensure that the sediment loading remained in suspension. Within the walls of the distribution cylinder were a number of orifices that controlled flow rate, by way of oversized tubing, to each of the test beds. A constant head was maintained above each orifice to deliver the required flow. Three types of permeable pavements were tested

(*a*) Boral formpave (PP1)
(*b*) Rocla Ecoloc (PP2)
(*c*) Grasspave (PP3).

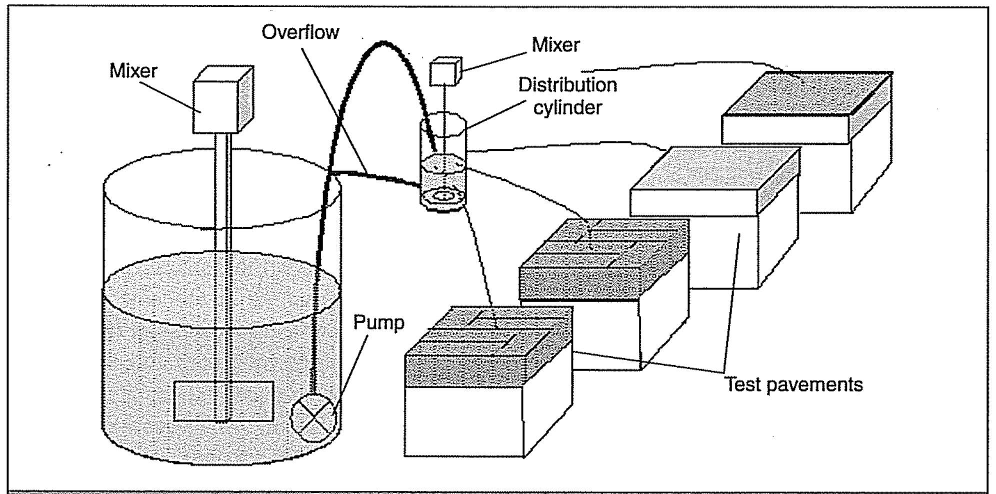

Figure 2. Schematic illustration of 'effective life' test rig

Four test beds were studied (Figure 3). Two test beds containing PP1 blocks were installed. One was subjected to the prototype equivalent of yearly surface cleaning with a stiff brush and vacuum to simulate a field street-sweeping device; the second PP1 test bed was not cleaned during the experiments. The other two test beds were PP2 and PP3, neither being cleaned during the experiments.

In practice, most permeable pavement installations will drain both rainfall falling directly on the paved catchment surface itself and surface flow from the connected upstream catchment. In this test programme, input flow rates to the pavement were calculated based on a permeable paved area and a connected impervious area of equal dimensions. Based on Adelaide's average annual rainfall of 580 mm, 7 h of $23{\cdot}3$ l/h constant flow delivers the equivalent of one year's runoff to the test pad each day. In terms of sediment loading, this provides a conservative simulation because the beds were laterally confined and the entire annual sediment load was applied to each test bed without possible bypassing. In Australian practice, pavements are likely to be bypassed during very high flows and therefore would receive lower annual sediment loads.

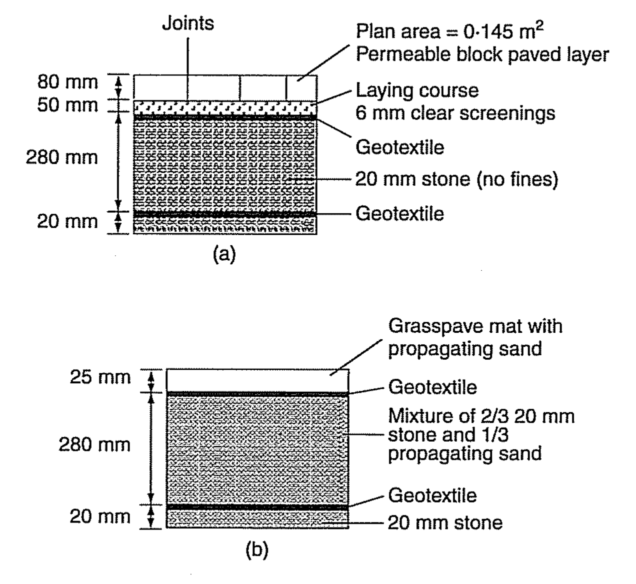

Figure 3. Cross-section of test bed arrangement: (a) PP1 and PP2; (b) PP3

Based on a review of available stormwater quality studies,[12] an average SS concentration of 200 mg/l was targeted for the input flow throughout the test. This SS level was considered to be at the upper end of the scale for runoff from developed catchments. The sediment used in the test was sourced from a sediment sump of a gross pollutant trap (GPT) at Mawson Lakes in Adelaide. The catchment feeding to the GPT has mixed land-use but is predominantly a residential suburb adjacent to the University of South Australia. The collected sediment was oven-dried, crushed and then passed through a 600 μm sieve to

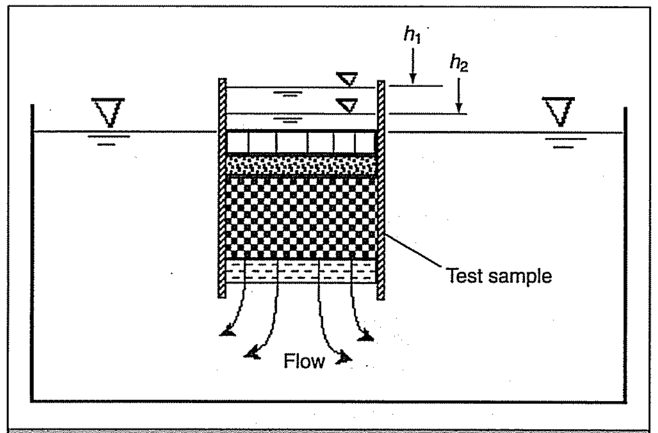

Figure 4. Details of hydraulic conductivity testing

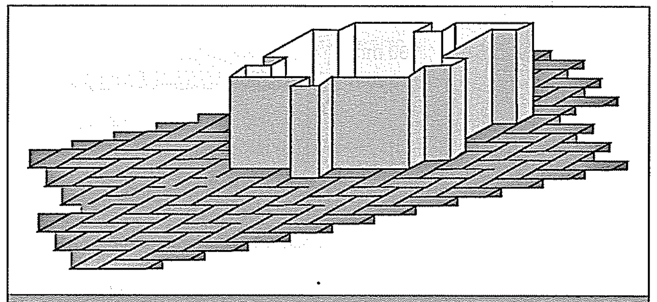

Figure 5. 'Fitted tank' apparatus for on-site surface infiltration rate testing

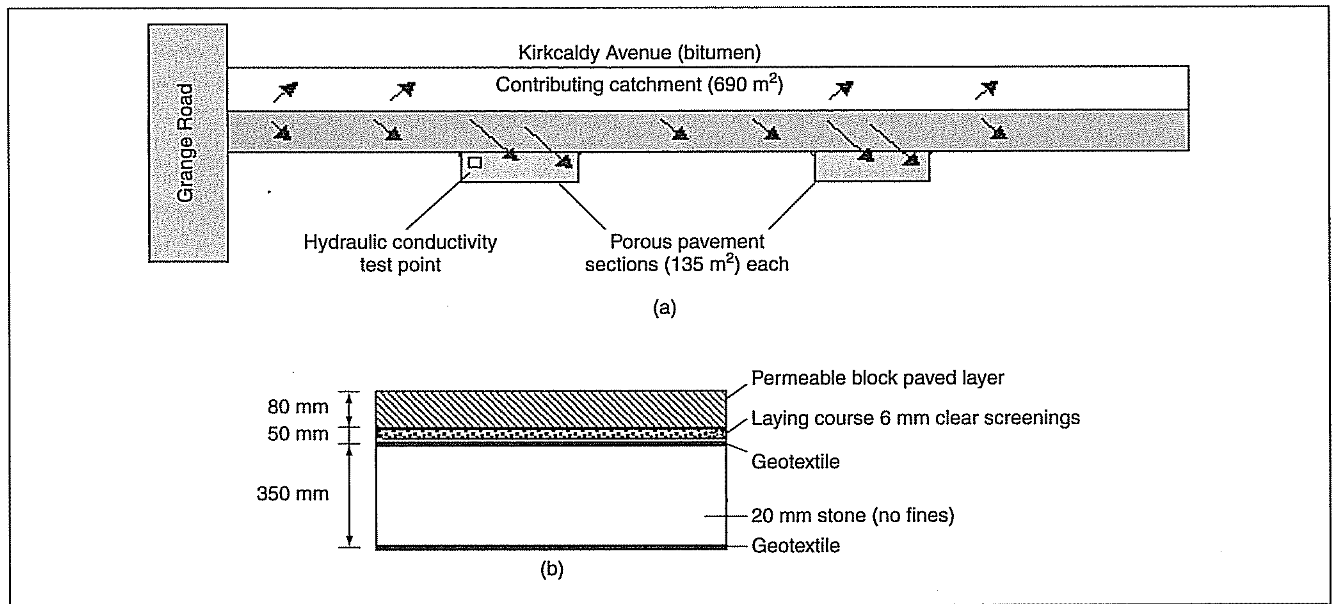

Figure 6. Kirkcaldy Avenue, Grange: (a) hydraulic conductivity test location; (b) cross-section of permeable pavement

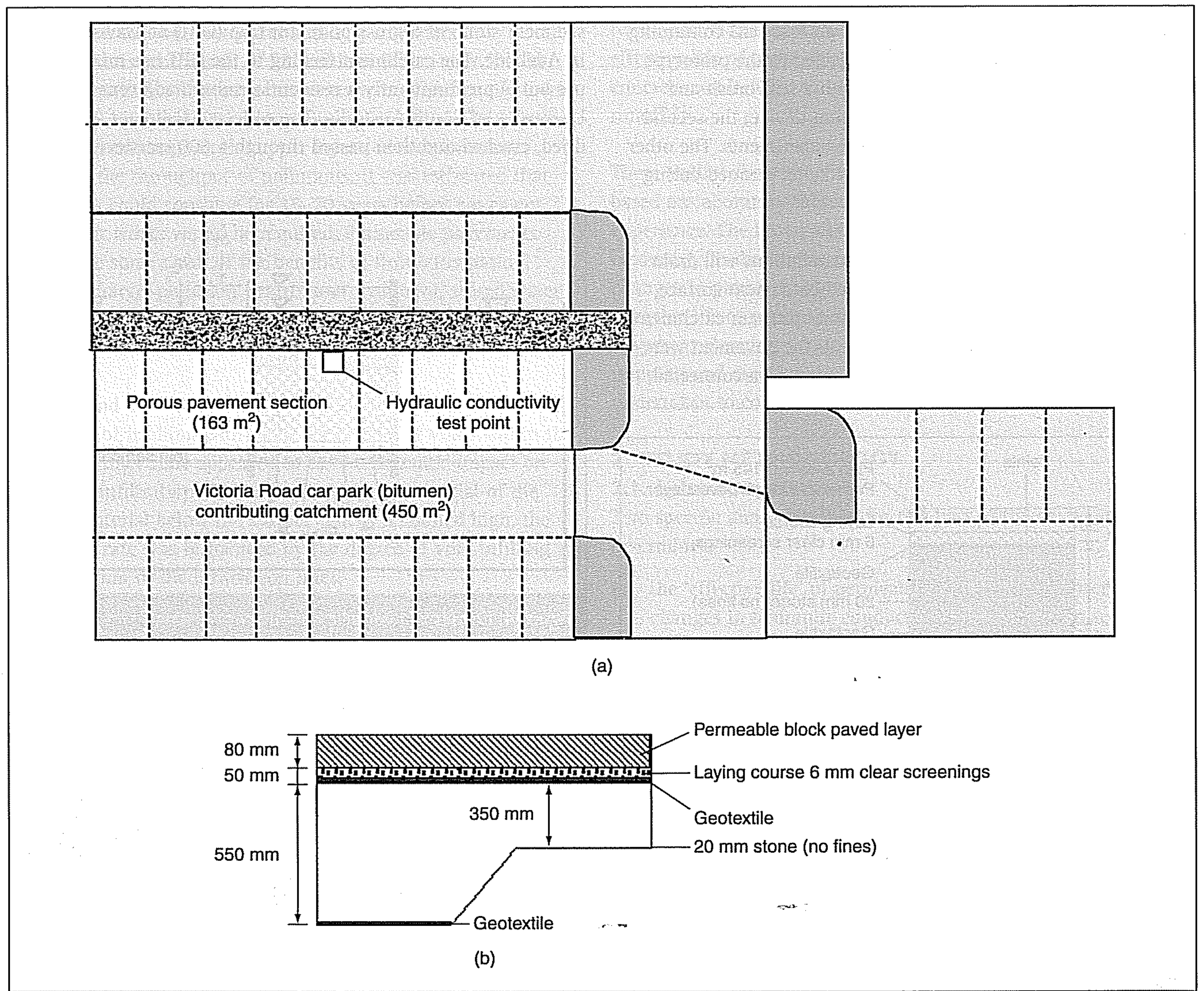

Figure 7. Victoria Road car park, North Haven: (a) hydraulic conductivity test location; (b) cross-section of permeable pavement

remove any gross pollutants. This was necessary to allow efficient delivery to the test beds by way of small orifices in the distribution cylinder. In Australia, because of the use of separate stormwater systems, suspended solids in stormwater are predominantly inorganic.

The hydraulic conductivity of the test beds was measured at five-day intervals to measure the degree of blockage and to minimise disturbance of the sediment retained in the permeable pavement structure during long-term testing. The models were submerged in a tank filled with mains water, becoming saturated as the water flowed slowly through the base of the test bed (Figure 4). When a predetermined head of water above the pavers was reached, the model was raised above the bath invert level. The time for the water level to drop to the top of the pavement was measured and the hydraulic conductivity calculated from

$$k = 2{\cdot}3\left(\frac{l}{t}\right)\log\left(\frac{h_1}{h_2}\right) \qquad (1)$$

where k is the coefficient of permeability (mm/h), l is sample length (mm), t is time (h), h_1 is initial head of water in the test bed (mm) and h_2 is the head of water in the test bed to which the water level has fallen after time t (mm).

While the falling head test for hydraulic conductivity does impact on the coefficient being measured by 'flushing' a portion of the trapped sediment through the test bed, care was taken to minimise this effect by lowering the test bed gradually into the bath and keeping the test driving head to a minimum.

Throughout each test run, the SS concentration of the input water was measured regularly to ensure the target sediment load of 200 mg/l was being delivered. The SS concentration of the outflow water was measured daily to determine the pollutant removal efficiency of the test beds. Samples of the water that seeped through the permeable pavement at the base of the test beds were taken and a measured volume was passed through 0·45 μm filter paper.

2.2. Field testing of surface infiltration rates

Controlled laboratory testing inevitably idealises the actual processes of pollutant build-up and pavement blockage, so on-site field testing was also conducted to better understand the clogging process and to gain further insight into the laboratory investigation. A series of surface infiltration tests was conducted at three field sites to gain an understanding of the decrease in hydraulic conductivity with time and the clogging rates of permeable pavements installed in the field.

Initially, four three-monthly tests were conducted at four sites in Adelaide over a 12-month period. Three test rigs were constructed to perform the testing. The test rig shown in Figure 5 is a 'fitted' tank used to test PP1 installations at Kirkcaldy Avenue (Figure 6) and Victoria Road car park (Figure 7). The tank extends approximately 25 mm into the joints between pavers. Similar rigs were constructed for testing the conductivity of PP2 pavements at Fletcher Lane, Woodville (Figure 8) and PP3 pavements at St Elizabeth Church, Warradale (Figure 9). The general location of the test sites in relation to the Adelaide central business district (CBD) is shown in Figure 10.

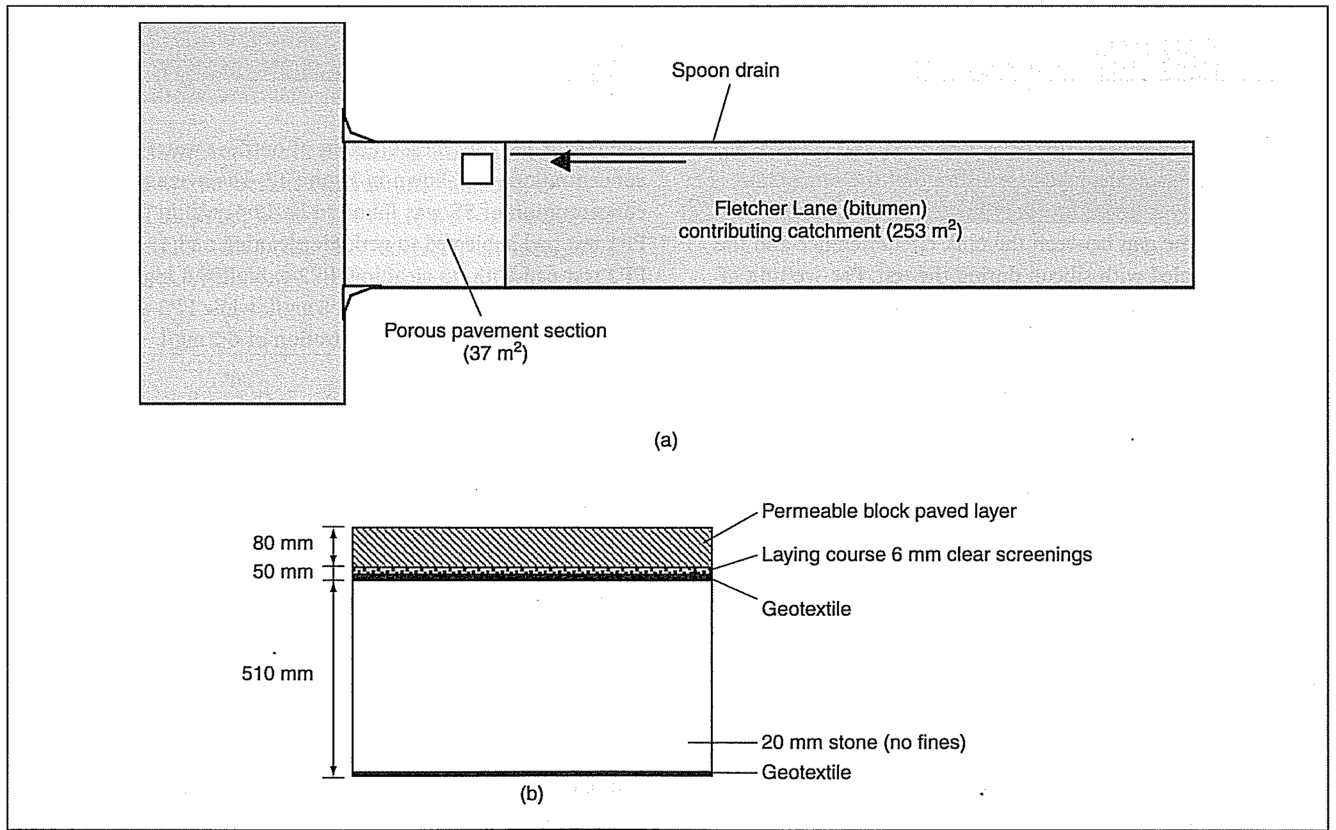

Figure 8. Fletcher Lane, Woodville: (a) hydraulic conductivity test location; (b) cross-section of permeable pavement

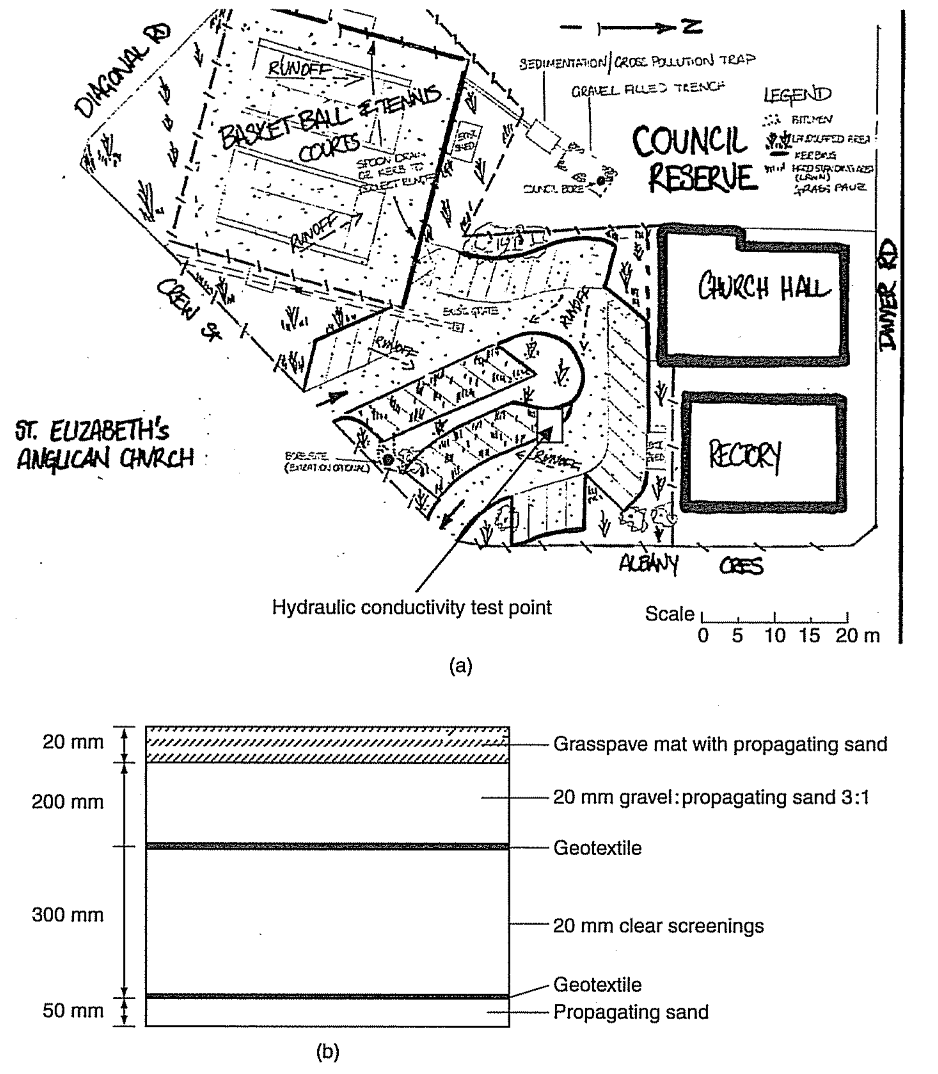

Figure 9. St Elizabeth Anglican Church, Warradale: (a) hydraulic conductivity test location; (b) cross-section of permeable pavement

The tanks were inserted into the blocks or grassed surface at the test locations. Care was taken to ensure that the same point at each location was tested on every occasion to maintain consistency. The gap between the tank circumference and the pavers was sealed with silicon during the test. Pre-wetting of the pavers and substructure was achieved by applying approximately 135 l to the test pad. This water was allowed to fully infiltrate. To begin the test, water was supplied to the test pad until the level reached 50 mm. The start of the falling head test was then recorded and the time taken for 50 mm of standing water to infiltrate was measured.

3. RESULTS AND DISCUSSION

3.1. Laboratory test results

It is estimated that an equivalent of 35 years of sediment input to the permeable pavement test beds was simulated in the test rig. Figure 11 shows the measured SS concentration of the input water delivered to the models over the equivalent of 420 months. The amount of sediment concentration was varied to simulate actual field conditions. While significant temporal variation in concentration about the mean value of 213 mg/l was observed, it should be noted that the prescribed sediment load was delivered to each test bed by the end of each simulated year.

The results of daily measurement of outflow water and SS concentrations are shown in Figure 12. The average outflow concentration of SS was found to be 12·4 mg/l in the case of the PP1 test pad subjected to periodic cleaning and 13 mg/l for the PP2 test pad with no cleaning. PP2 exhibited a higher average outflow SS concentration of 22·8 mg/l, while PP3 showed the lowest average outflow concentration of 6·2 mg/l.

Cleaning the surface of PP1 at the end of each simulated year made only 12·4% difference to the average SS concentration in the outflow. It is possible that the low impact of cleaning could be due to the small apertures between the pavers in PP1. The cleaning mechanism utilised would only have an effect on the upper few millimetres of the apertures; sediment collected at the geofabric layer would thus be unaffected by cleaning.

A total of 1110 g of sediment was applied to each of the PP1 test beds, while only 70 g passed through with the outflow water. The average sediment retention of this permeable pavement over the 35-year simulation was therefore 94%. PP2 and PP3 test beds had retention rates of 89% and 97%, respectively.

Hydraulic conductivity through PP1 was predictably high at the commencement of the test, bearing in mind that the pavement was constructed with apertures containing 6 mm screenings. Figure 13(a) shows the decline in hydraulic conductivity throughout the 35 years, from $1·7 \times 10^{5}$ to $6·5 \times 10^{4}$ mm/h (average of both PP1 test beds). This represents an average reduction of 59%. While every effort was made to construct

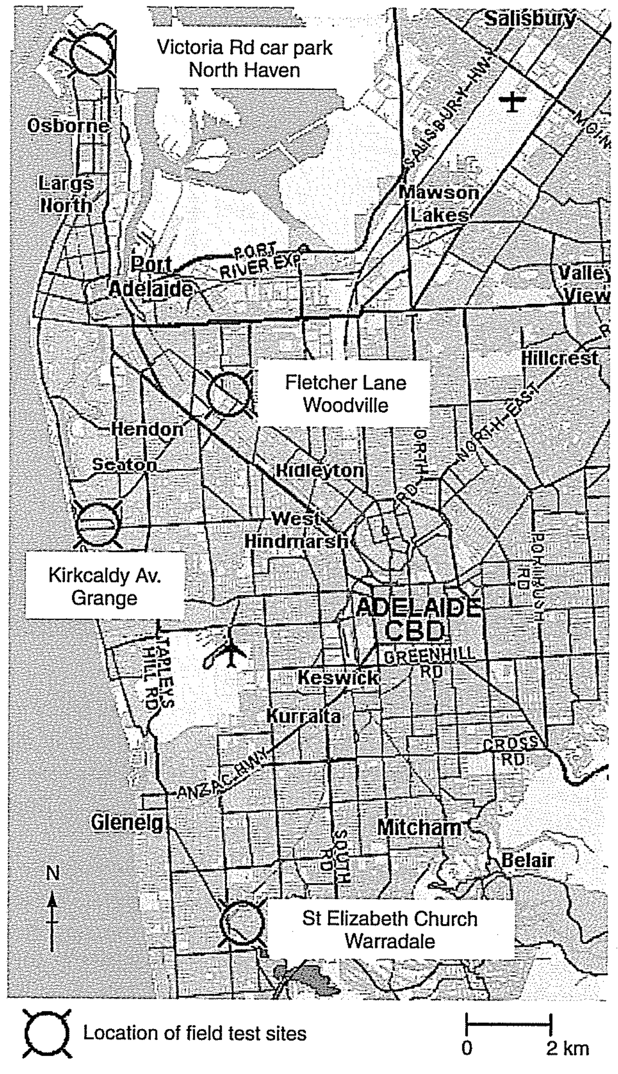

Figure 10. General location of field test sites in relation to Adelaide CBD

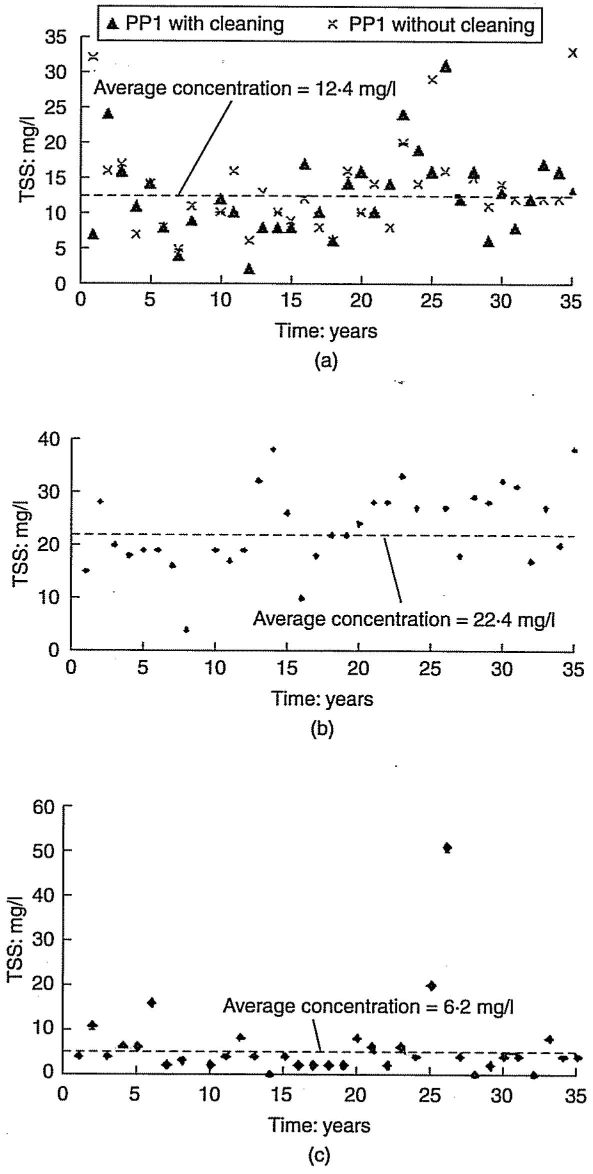

Figure 12. Total suspended solid concentration in outflow solution: (a) PP1; (b) PP2; (c) PP3

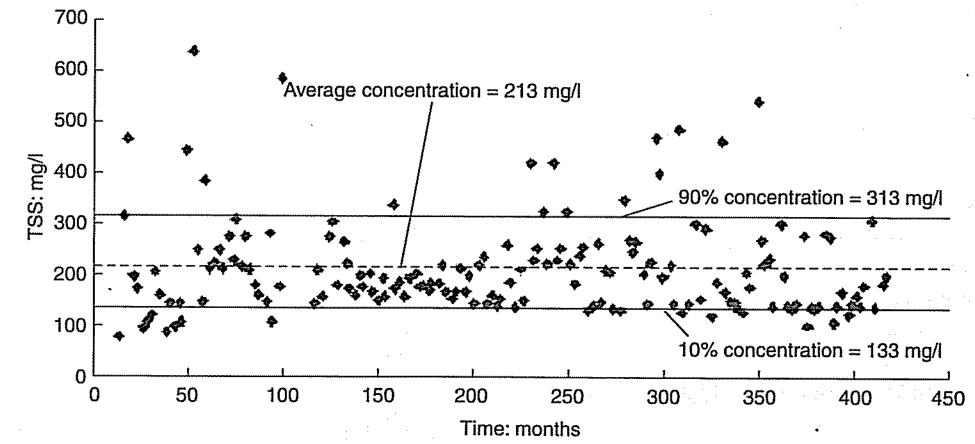

Figure 11. Total suspended solid (TSS) concentration in input flow

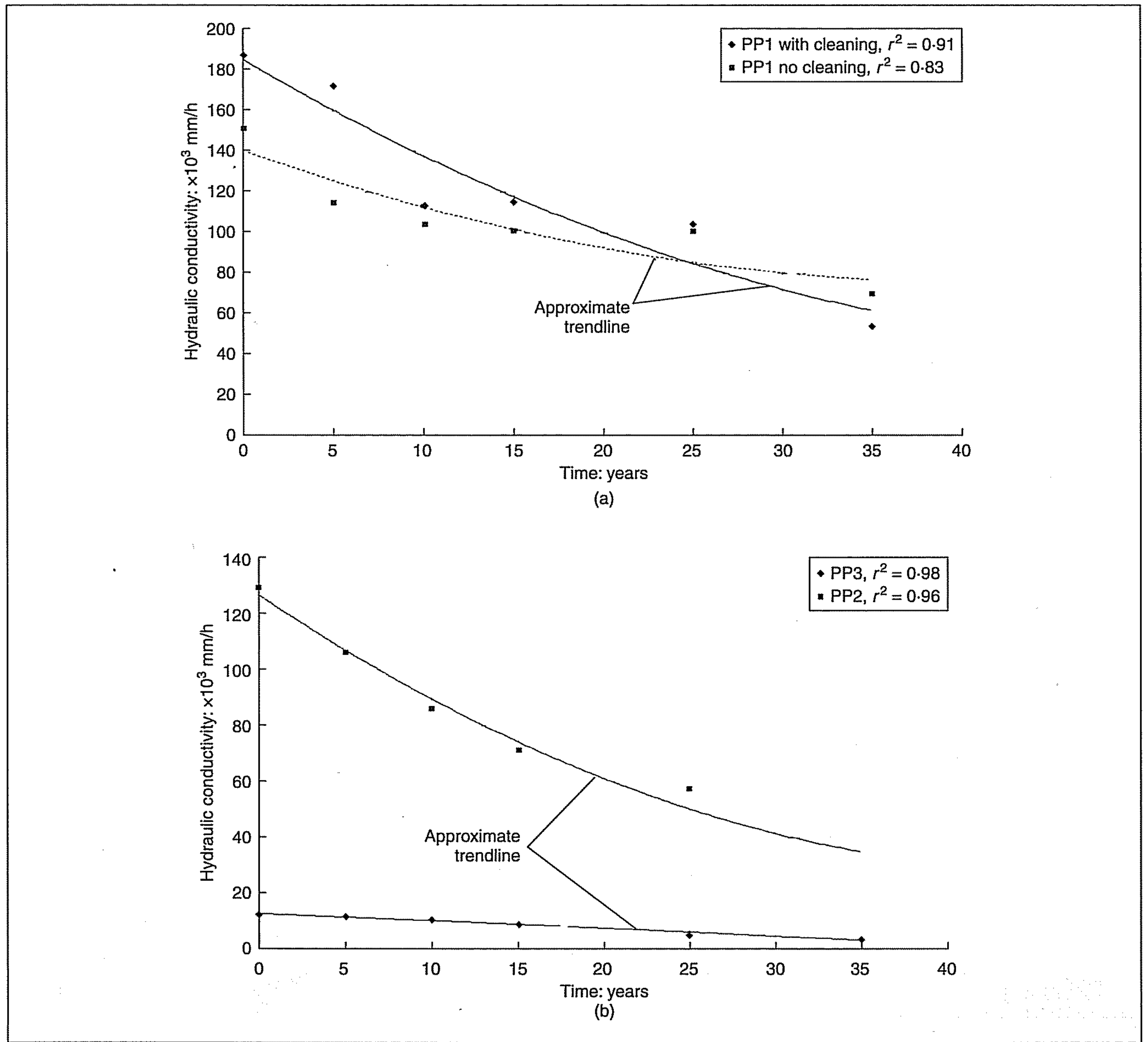

Figure 13. Changes in hydraulic conductivity over time: (a) PP1; (b) PP2 and PP3

identical beds, the difference between initial hydraulic conductivity values can only be explained by suspected slight variations in material and construction. Conductivity through the test beds converged as the tests progressed. The trendlines shown in Figures 13(a) and 13(b) have a high regression coefficient.

The hydraulic conductivity of PP2 was similar to that of the PP1 test beds, although it remained slightly lower throughout. PP3 exhibited hydraulic conductivities an order of magnitude lower again than the other three pavements under test. It is believed that this was due to the propagating sand content in the base material and within the PP3 mat. Propagating sand is the term used to describe the soil in the Grasspave apertures in which grass or other vegetation grows. Over the 35-year simulated test, PP2 and PP3 experienced declines in hydraulic conductivity of 68% and 75%, respectively (Figure 13(b)).

3.2. Field test results

Results from surface infiltration tests performed at the four field sites are summarised in Table 1 and shown in Figure 14. The rate of infiltration was exceptionally high at Victoria Road car park and is thus not shown in Figure 14. Adequate surface water heads could not be maintained to allow hydraulic conductivity testing, even with the maximum inflow rate of 3 l/s that could be applied by the test equipment. These exceptionally high infiltration rates were due to the underlying sandy soils in the area and low-level sediment concentration in the surface runoff.

Date	Rate of surface infiltration: mm/h			
	Kirkcaldy Ave.	Victoria Rd	Fletcher Lane	St Elizabeth Church
31/03/2000	900	High*	2571	614
31/05/2000	360	High*	1241	360
17/08/2000	168	High*	583	47
13/11/2000	143	High*	947	703
26/04/2001	211	High*	592	202
4/10/2007	24	High*	295	302

* Too high to maintain any head of surface water in test rig, up to inflow rates of >3 l/s

Table 1. Field test surface infiltration results

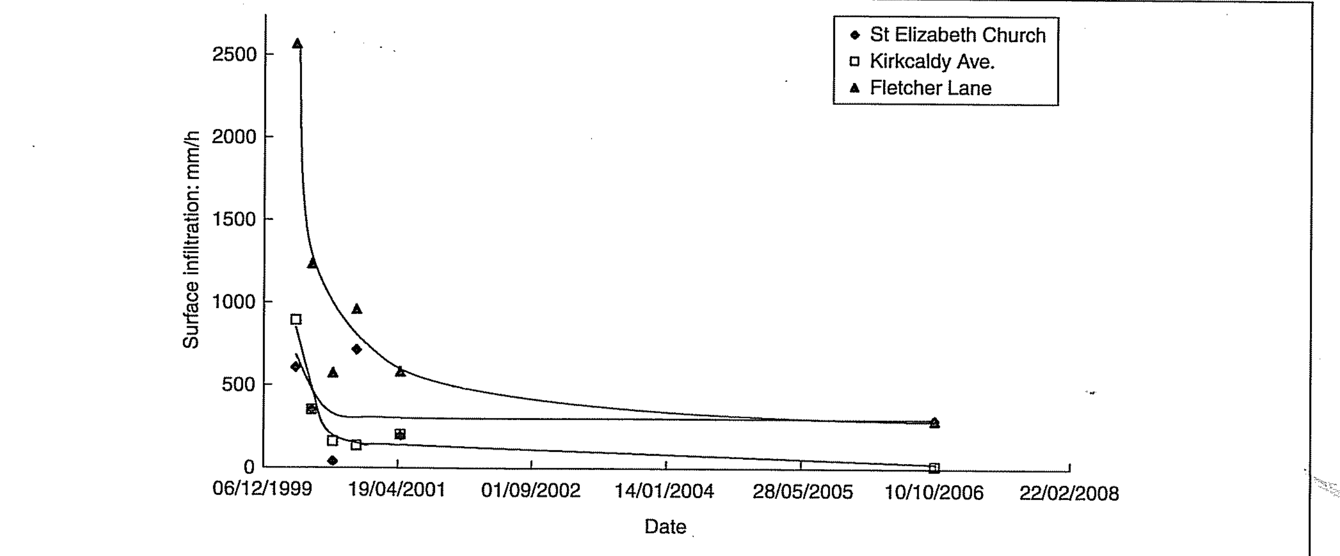

Figure 14. Reduction in surface infiltration rate over the monitoring period (the hydraulic conductivity at the Victoria Road site was greater than 3000 mm/h and is not shown in figure, see Table 1)

At all other field locations, the rate of 'clogging' was high, causing blockage of the drainage paths through the paving. Infiltration rates dropped to approximately 8% of the initial rate at the St Elizabeth Church site over the first two months of testing. At Kirkcaldy Avenue and Fletcher Lane, reductions in infiltration rates to 19% and 23% respectively of the initial values were observed. At all locations, the rate of reduction was seen to decrease over the period of monitoring (Figure 14). The trend lines drawn through the three sets of data in Figure 14 indicate that infiltration rates were approaching minimum values at all sites.

When infiltration rates reported for the three field sites in March 2000 (Figure 14) are compared with the initial hydraulic conductivity values measured in the laboratory programme (Figures 13(a) and (b)), considerable differences are revealed (see Table 2). The main reason for this is the accumulation of sediment that occurred between the time of installation and the period of field testing.

It should be noted that the positions of the test points at each location (see Figures 6 to 9) were specifically chosen to determine the maximum likely rate of decline in infiltration. In each case, the rig was placed at the upstream end of the permeable pavement where the majority of polluted runoff enters the system. As these regions become more clogged with sediment and organic matter, runoff passes over onto downstream areas with much higher infiltration rates. In this way, a 'clogging front' is observed to develop. At the Kirkcaldy Avenue, Fletcher Lane and St Elizabeth Church sites, the clogging front was observed to pass over the test location during the course of the monitoring programme. At Kirkcaldy Avenue, this 'clogging front' appears to be expanding, without maintenance, at a rate of about 5 m^2/year. By late 2007, the clogging front had spread to two-thirds of the total area and the infiltration rate had reduced significantly (to 24 mm/h). However, where the clogging front was not apparent the infiltration rate was still moderate (300 mm/h).

A further important observation, brought to light by examination of the clogging front at Kirkcaldy Avenue, was the process of blockage. This blockage was due to infilling of gaps between the masonry blocks by a mixture of sediment, coarse sand and organic matter. This differs from the relatively fine sediment that was retained by the geotextile layer in the laboratory programme. However, this appears to be trapped and retained within the grass matrix above the PP3 units, and was removed with regular grass mowing and removal of debris.

The performance of permeable paving receiving surface runoff therefore involves two levels of sediment accumulation. The first is coarse sediment retained in a relatively small upper horizon of a typical permeable pavement installation. Clogging

	Infiltration rate: mm/h		
	PP1	PP2	PP3
Laboratory hydraulic conductivity (after 35-year simulation)	60 000	34 000	4 000
Field hydraulic conductivity (aged paving at the end of monitoring period)	200	600	5

Table 2. Laboratory and field infiltration rates

of this material without maintenance can effectively cut off fine sediment flow to the lower (filter) layers. The second is fine sediment retained on geotextile layers in the main body of a typical installation. Clogging of this material proceeds at a relatively slow rate, ensuring – with correct design – longer lifespans. Prevention of the first type of clogging (coarse sediment) is essential to maintain the effective life of permeable pavements.

It was not possible to simulate wind-borne sediment in the laboratory experiments, and this may explain some of the differences between the laboratory and experimental results.

4. CONCLUSIONS

This study investigated the performance of three stormwater infiltration pavement systems through both laboratory and field trials. The systems tested were Formpave (PP1), Rocla Ecoloc (PP2) and Grasspave (PP3). The main outcomes of this research include simulated 'effective life' of the pavers through sediment loading on test beds, measurement of SS concentration in the outflow and field surface infiltration rate testing.

The effective life testing stage of the pavers was conducted by simulating 35 years of sediment loading to the permeable paving test beds. Over the period simulated, laboratory results showed reductions of 59, 68 and 75% in the hydraulic conductivity of PP1, PP2 and PP3 respectively. No significant difference in SS concentration was observed in the outflow when the test bed was subjected to surface sweeping and vacuuming. The average sediment retention of the permeable pavement over the 35-year simulation for PP1, PP2 and PP3 was 94, 89 and 97%, respectively.

Hydraulic conductivity monitoring in the field showed that, at the Victoria Road site the permeable pavement was performing in accordance with the laboratory results. At the other three field sites, the much lower infiltration rates were attributed to clogging by sediment and organic matter as the measurement locations were located at the upstream end of the permeable pavement where the majority of stormwater runoff enters the system. Prevention of this form of clogging is essential to maintain the effective life of permeable pavements.

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