A Report on a Testing Programme

Appraisal of the Performance of Plock Paving

With and without Geotextile in the Sub-base

Authors
J Mullaney
C Jefferies

Summary of Report

This research project was undertaken to determine whether or not an upper geotextile within a permeable paving system provides beneficial water quality and hydraulic properties for Marshalls Plc using Priora permeable paving blocks. A field study was carried out on ten test rigs to determine the removal properties of metals and engine oil within paving areas. The results of tests from the rigs with a geotextile were compared to the results those with no geotextile.

The project comprised ten years simulation of pollutants flowing on to the block paving carried out in 3 simulation periods of 1 year, 2 year and 7 years equating to 1, 3 and 10 years equivalent of pollutants. All sample analysis was carried out by Severn Trent Laboratories.

Analysis of results after 10 years of application of metal pollutants showed high metal removal rates for all 5 metals applied with 75-95% removed. Although the rigs with a geotextile removed a greater percentage of metals compared to the test rigs without a geotextile, the differences were insignificant. Thus, on the basis of application of the equivalent ten years of heavy metals contaminants, it can be concluded that the presence of the geotextile was not beneficial.

The tests using engine oil showed a similar variable behaviour for the first two sets of application. In contrast to the removal of metals, the overall removal of oils declined over the ten years (equivalent) of application. On average after 10 years, removal of oil in the rigs with geotextile (82%) was better than without (75.5%). There is again significant variability in the results and there is insufficient information to conclude whether the geotextile is beneficial. However it is considered highly likely that the differences would be small with longer test periods or more applications. Further testing in this area is justified.

The project was carried out with the assistance of with Lesley Samson, Msc student at University of Abertay, Dundee.

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1 Introduction

The purpose of this research was to determine whether or not an upper geotextile within a permeable paving system provides water quality and hydraulic benefits using Marshalls Priora permeable paving blocks. A literature review was conducted to determine if a similar study had been done before and to determine the pollutants which should be tested. From this literature review it became evident that no such study had taken place; there were studies with or without geotextiles but none testing both simultaneously.

The literature review identified the metals present in road runoff which should be replicated in the testing programme. Table 1 shows the concentrations of metals present in highway runoff while Table 2 shows the metals present in soil-forming rocks and other natural minerals. In order to overcome any potential problems with background concentration interference, the concentrations of pollutants to be applied to the paving rig were double typical highway runoff concentrations.

It was also evident from the literature review that hydrocarbons in the form of engine oil should be applied to determine if the geotextile has higher removal.

In the test programme undertaken, a total of ten years of metal and oil loading was applied to areas of paving in batches of 1, 2 and 7years.

Pollutant	Concentration (mg/l)	Concentration Applied (mg/l)
Cadmium	0.012	0.024
Copper	0.028	0.056
Lead	0.399	0.798
Nickel	0.144	0.288
Zinc	0.479	0.958

Table 1 Typical concentrations of pollutants in Highway Runoff

Pollutant	Ultramalic igneous	Basaltic igneous	Granitic igneous	Shales / Clays	Black shales	Lime-stone	Sand-stone
Cadmium	0.05	0.2	0.15	1.4	1.0	0.05	0.05
Copper	15	90	15	50	70	4	2
Lead	1	6	18	20	30	9	12
Nickel	2000	140	8	68	50	20	2
Zinc	40	110	40	90	100	20	16

Table 2 Concentrations (mg/kg) of trace elements in various soil-forming rocks and other natural minerals (Sparks, 1995)

2 Methodology

A total of ten test rigs 1m x 1m x 0.5m deep were constructed and located at a test site at Dundee airport. Each test rig was constructed using marine plywood and had a clear acrylic front 'window' for inspection. The rigs at the site are shown in Figures 1 and 2. A perforated pipe was installed at the base of the rig leading to a v-notch for drainage of the paving panels, flow measurement and sample collection.

Figure 1 Test rig

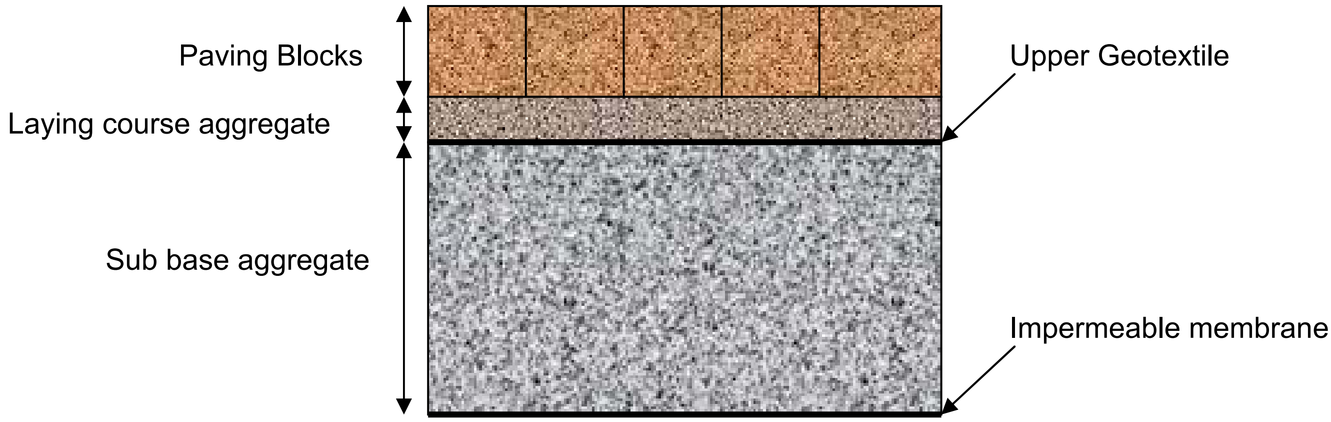
Figure 2 Test site

2.1 Construction

The porous paving system was constructed in accordance with Marshalls's specification for their Priora Paving system, with design methodology and base specification in accordance with BS 7533-13:2009, BS EN13242:2002 and other standards. The detailed sections of the construction are shown in Table 3 and Figure 3.

Panels with Geotextile	Panels without Geotextile	
• One layer Priora paving block 200x100x80mm • 50mm depth of 2/6.3mm laying course graded aggregate • Upper permeable membrane • 350mm depth of 4/20 sub base aggregate • Impermeable membrane liner	• One layer Priora paving block 200x100x80mm • 50mm depth of 2/6.3mm laying-course graded aggregate • 350mm depth of 4/20 sub base aggregate • Impermeable membrane liner	**TOP** **BOTTOM**

Table 3 Design Specification



Rig Number	Construction	Test
1	No Geotextile	Metals
2	Geotextile	Metals
3	No Geotextile	Oils
4	Geotextile	Oils
5	No Geotextile	Control
6	Geotextile	Control
7	No Geotextile	Metals and Oils
8	Geotextile	Metals and Oils

Table 4 Rig Details

Figures 4-6 below show the various stages during the construction of the paving rig. During the laying of the sub-base, the aggregate was compacted in layers of 50mm to obtain as good a representation of compaction in the field. The laying course aggregate was also compacted before the laying of the paving blocks. The paving blocks were laid in the standard herringbone pattern.

Figure 4 Sub base

Figure 5 Aggregates with Geotextile

Figure 6 Paving rig with geotextile

2.2 Rainfall simulation

Rainfall was simulated using a branch sprinkler system fed from a 1200 litre tank; 1200 litres was used as the UK annual rainfall is 1201.3mml (Met office, 2010). The rainfall was applied to the paving area by gravity until the tank was emptied.

Following application of the ‘rainfall’, the contaminated water passed through the paving. It was collected by the perforated pipe and conveyed into the sampling pot and over the v-notch weir. The depth of flow over the v notch was measured using Buhler Montec flow monitors to enable a flow rate and volume to be calculated using British Standard V notch equations.

Samples were taken every two minutes from the sample pot using Epic automatic samplers. The samples were consolidated and 3 composite samples were taken for analysis.

Figures 7 to 10 show the various stages of the application of the flow, the sampling and the measurement.

Figure 7 Rainfall Simulator

Figure 8 Underside of rainfall simulator

Figure 9 Rainfall Simulation

Figure 10 Sampling Chamber

Figure 11 Monitoring set-up

2.3 Pollution Application

Metals, oils and sediment were applied to separate rigs to determine whether or not the water quality improved with the inclusion of the geotextile. Two rigs were kept as controls with only water applied, two rigs had metals applied, two had oil applied, two were used to determine clogging levels and the final two had both oil and metals applied to the surface. The metals were bought in solution from a commercial supplier at the required concentrations mentioned in Table 1. The volume required of each metal was measured out and poured into the water tank.

2.3.1 Metals

The metals applied were cadmium, lead, nickel, zinc and copper. A concentrated solution containing a ‘cocktail’ of metals was added to the water tank in soluble form. The water in the tank was then mixed before the solution was applied to the paving area. The total loads of each metal were as shown in Table 5.

Pollutant	Yr 1 Load (mg)	Yr 2 Load (mg)	Yr 7 Load (mg)	Total Load 10 years total (mg)
Cadmium	28.8	57.6	201.6	288
Copper	67.2	134.4	470.4	672
Lead	957.6	1915.2	6703.2	9576
Nickel	345.6	691.2	2419.2	3456
Zinc	1149.6	2299.2	8047.2	11496

Table 5 Metals Loadings

2.3.2 Oils

A light motor oil was used in the experiments to best represent oil drips from motor cars and the volumes used are given in Table 3. Oil was dripped onto the paving area using a bucket with 3mm holes in the bottom. To ensure all the oil was dripped onto the paving area a plastic bucked was used. The bucket was also checked after application to ensure no oil was remaining in the bucket. 1 years oil was applied before rainfall simulation, in the case of 2 years volume of oil the oil was applied in 2 batches, 1 before the test run began then another after the tank was half empty. The water was turned off to allow oil application, once applied the remaining water volume was applied. For the 7yr run the water was stopped every 15 minutes to allow one year of oil to be applied, once the oil had been applied the rainfall simulator was placed back onto the paving unit and water ran for another 15 minutes. This was done until 7 years of oil had been applied.

Figure 12 Oil application

Figure 13 Oil application bucket

Event (yrs)	Oil Applied (litres)
1	0.6
2	1.2
7	4.2
Total of 10 years	6

Table 6 Oil volumes

2.4 Flow Monitoring

Buhler Montec flow monitors were set up to read the depth of flow over the v-notch every 2 minutes. This depth could then be used in an equation to determine the flow volume which has passed through the paving test rig. Table 7 shows the flow volumes from the 3 test runs for each of the 8 boxes tested at present. The tank holds 1200 litres, as it can be seen in Table 7 the volumes from the outlet of the box are approximately 300 litres less. This is due to the outlet pipe of the tank being slightly higher than the tank base making some of the water remain in the tank and due to the outlet pipe of the test rig being raised of the bottom of the test rig. It was determined that the base of the test rig would retain 22 litres. There is also some discrepancy with the volume of water in the tank as there is no marker on the tank to indicate 1200 litres, therefore on the filing of each tank it was filled to a recognisable mark on the tank to ensure the same volume was applied. The actual volume applied could therefore be less than the 1200 estimated.

	Box Number							
Run Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Yr 1	882.71	845.70	718.97	910.83	958.20	960.30	918.49	928.85
Yr 2	876.28	889.40	953.71	967.72	897.97	935.27	952.89	937.95
Yr 7	916.96	937.61	969.77	900.04	903.07	904.47	957.41	910.30

Table 7 Flow Volumes

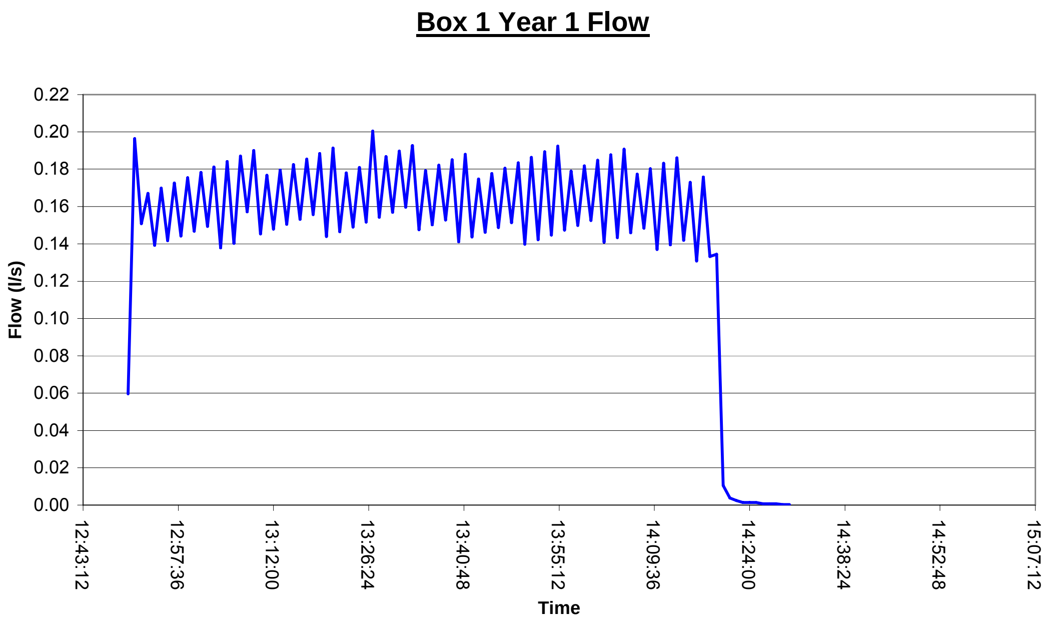


Figure 14 Flow Graph for Box 1 Yr 1

3 Geotextiles

Currently the geotextile used by Marshalls PLC for permeable paving construction is Terram 1000. There are five main functions of a geotextile in this application: separation, filtration, drainage, protection and reinforcement. Geotextiles are used within permeable paving structures to have at least two of these functions, usually more. A review by UWTC looked at other geotextiles and compared these to the current geotextile used by Marshalls PLC.

Geotextiles can be characterised as being 'woven' or 'non woven'. Woven geotextiles are formed by interlacing two or more sets of yarns, fibres or filaments' where they pass each other at right angles. Non-woven geotextiles are not as strong as woven but they possess better infiltration and separation properties (Cook, 2003). Over 70% of the geotextile manufacturers reviewed supply non woven geotextiles for use within permeable paving structures due to their filtration and separation properties.

Of the geotextiles reviewed, only two stated that they could provide specific geotextiles designed for use within permeable pavements; Terram, the geotextile currently used by Marshalls and Inbitex & Permavoid used by Hanson Formpave, which are also the manufacturers of Althon Ltd's SEL Sudstex Permafilter, Charcons Permafilter and Blockleys Smart Geotextile.

The review showed that there is little difference between Terram 1000 and the geotextiles supplied by other manufactures. Geotextiles made by Permavoid are more efficient at coping with catastrophic oil spillages (maximum of 6 litres per $10m^2$), as they have been designed specifically for trapping hydrocarbons.

4 **Results**

4.1 Summary of Results

After 7 years (total of 10 years) worth of metals had been applied to the surface the paving structure showed more than 80% removal rate for all five metals (cadmium, nickel, copper, lead and zinc). Removal of copper, nickel, zinc and lead all exceeded 90% in the case of the test rigs with a geotextile. The test rigs incorporating a geotextile removed a greater percentage of metals compared to those without a geotextile through all three of the test runs (1yr, 2 yr and 7yr), but the difference was minimal. Oil removal for years 1 and 2 was over 90% for all test rigs excluding Rig 3 (oil only, no geotextile). After 7 years of testing the two test rigs with no geotextile (Rigs 1 & 7) had a greater percentage than the corresponding rigs.

4.2 Calculations

To determine the percentage removal of metals in the paving test rigs the concentration were first changed to mg/l to determine the volume to be added to the tank of water.

Using the example of 1 years application of cadmium:

Concentration applied
Concentration of cadmium required = 0.024mg/l.
NB. 1ml=1mg.
Load required = concentration x volume of water
= 0.024 x 1200 =28.8mg

Mass of solution used = 28.8mg is the same as 28.8ml.

Percentage removal is determined as follows:
The following calculation is based on an average outflow concentration of 2.7µg/l.
Concentration applied = 0.024mg/l. This = 24µg/l, Concentration Out = 2.7µg/l
Percentage removal=(conc in-conc out)/conc in x 100
=(24-2.7)/24 x 100
=88.75%
Note, this calculation assumes that the outlet concentration is sensibly constant throughout outflow. Figure 14 shows that this is a reasonable assumption.

Determination of the percentage removal of oil within the paving test rig followed a similar logic to that for metals. First the mass of oil applied was determined.

<u>Using the example of 1 years application of oil:</u>

Mass= volume of oil x density of oil
= 0.6 litres x 860mg/l
=516mg.
The tank used for the oil tests had a volume of 741 litres

Initial concentration applied = mass/tank volume
= 516/741 mg/l
=696.4 μg/l
The following calculation is based on an average outflow concentration of 20μg/l.

Percentage removal= (conc in-conc out)/conc in x 100
=(696.4-20)/696.4 x 100
=97%

4.3 Results Tables

The results shown in the tables below are based on an average of the three samples taken. All the individual results can be seen in Appendix B. NG indicates the test rig did not have a geotextile and G indicates that it did have a geotextile.

Cadmium

	YR 1	YR 2	YR 7
Metal NG	88	93	88
Metal G	81	94	91
Metal and Oil NG	84	88	93
Metal and Oil G	89	92	98

Nickel

	YR 1	YR 2	YR 7
Metal NG	85	90	89
Metal G	70	89	92
Metal and Oil NG	71	84	95
Metal and Oil G	85	92	91

Copper

	YR 1	YR 2	YR 7
Metal NG	55	82	84
Metal G	40	77	86
Metal and Oil NG	27	77	81
Metal and Oil G	57	79	83

Zinc

	YR 1	YR 2	YR 7
Metal NG	83	88	86
Metal G	67	90	90
Metal and Oil NG	73	84	83
Metal and Oil G	77	89	89

Lead

	YR 1	YR 2	YR 7
Metal NG	86	91	93
Metal G	77	93	95
Metal and Oil NG	79	88	90
Metal and Oil G	90	95	94

Oil

	YR 1	YR 2	YR 7
Oil NG	97	81	77
Oil G	92	91	77
Oil and Metal NG	96	94	74
Oil and Metal G	91	90	87

Table 8 Percentage Removal of Metals and Oil

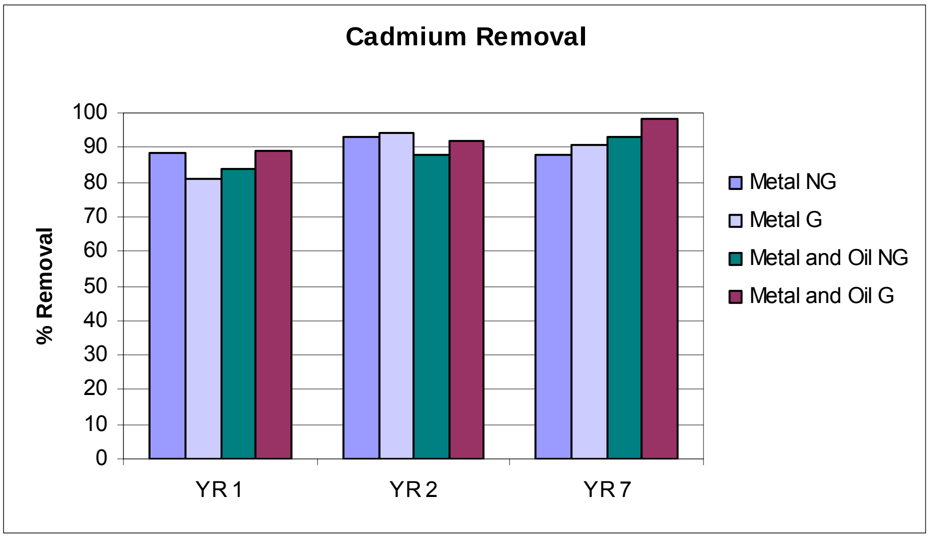
	pH levels		
	Yr 1	**Yr 2**	**Yr 7**
Metal Water Tank NG	6.8	6.9	6.6
Metal Water Tank G	7.4	6.9	6.2
Metal NG	9.1	8.7	7.6
Metal G	9.6	9.2	7.6
Oil Water Tank NG	7.8	7.9	7.4
Oil Water Tank G	7.9	7.8	7.8
Oil NG	9.3	8.9	8.7
Oil G	7.6	9.3	8.4
Control Water Tank NG	7.7	7.7	7.6
Control Water Tank G	7.9	7.9	7.6
Control NG	9.3	9.0	8.9
Control G	9.3	9.0	8.5
Metal and Oil Water Tank NG	7.5	7.1	6.7
Metal and Oil Water Tank G	7.2	6.9	6.9
Metal and Oil NG	9.2	8.5	7.7
Metal and Oil G	9.4	8.7	8.2

Table 9 pH before and after testing

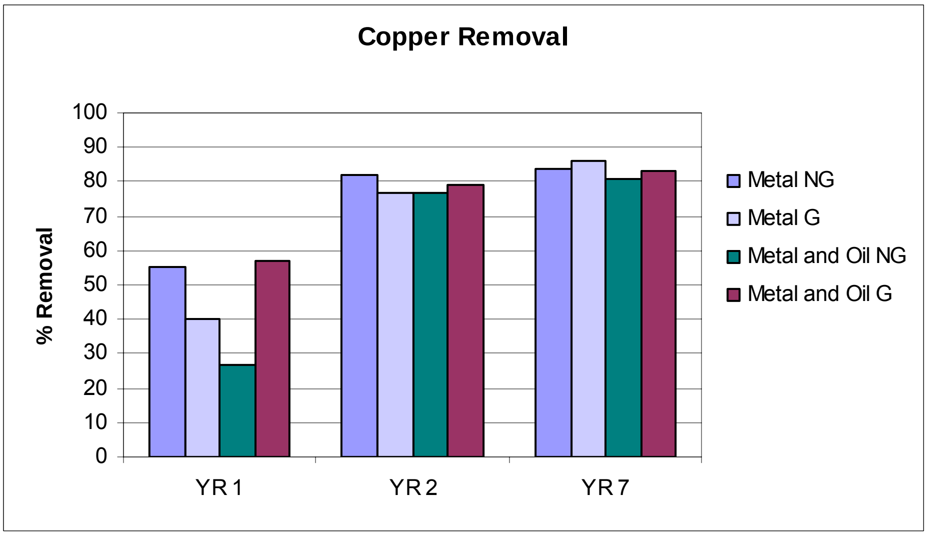
	Susupended Solids (mg/l)		
	Yr 1	Yr 2	Yr 7
Metal Water Tank NG	1	3	1
Metal Water Tank G	1	2	2
Metal NG	158	78	57
Metal G	566	116	64
Oil Water Tank NG	4	1	2
Oil Water Tank G	1	4	2
Oil NG	321	179	295
Oil G	1010	159	202
Control Water Tank NG	6	5	3
Control Water Tank G	1	1	3
Control NG	197	165	98
Control G	119	100	66
Metal and Oil Water Tank NG	2	3	15
Metal and Oil Water Tank G	1	3	2
Metal and Oil NG	491	144	189
Metal and Oil G	419	184	242

Table 10 Suspended Solids concentrations before and after testing

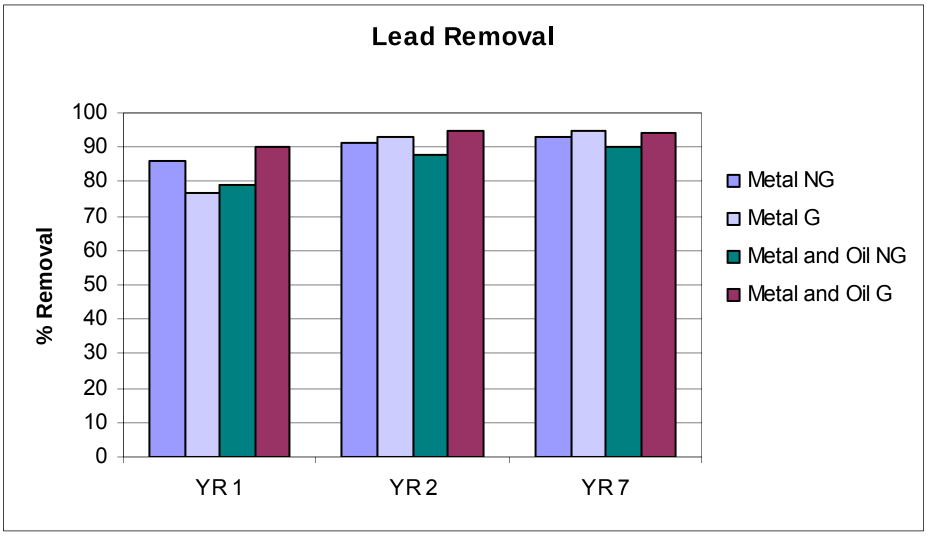
4.4 Graphs



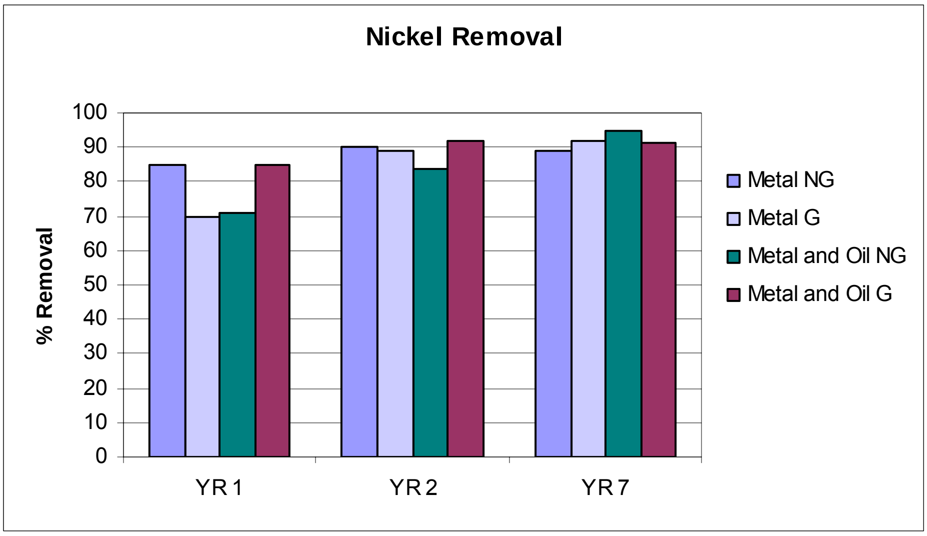
Cadmium Removal
% Removal
100
90
80
70
60
50
40
30
20
10
0
YR 1
YR 2
YR 7
Metal NG
Metal G
Metal and Oil NG
Metal and Oil G

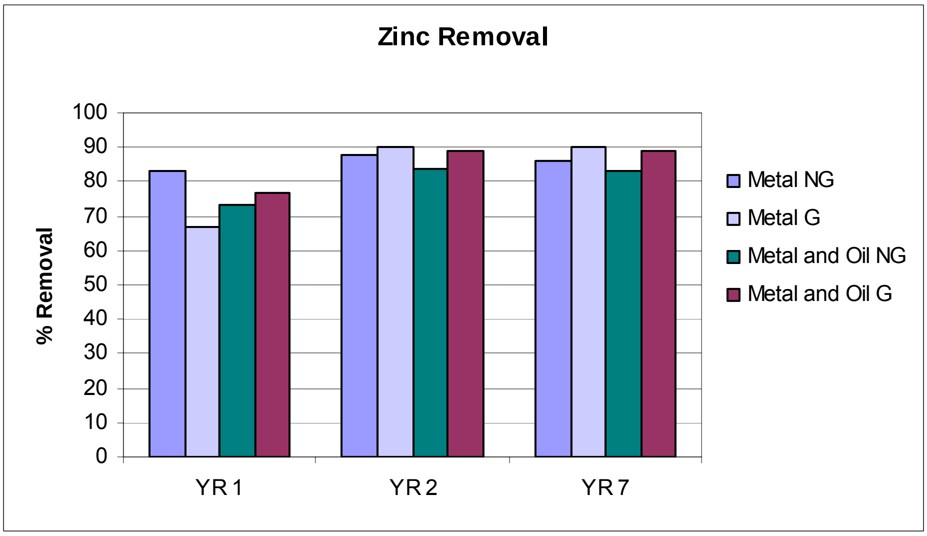


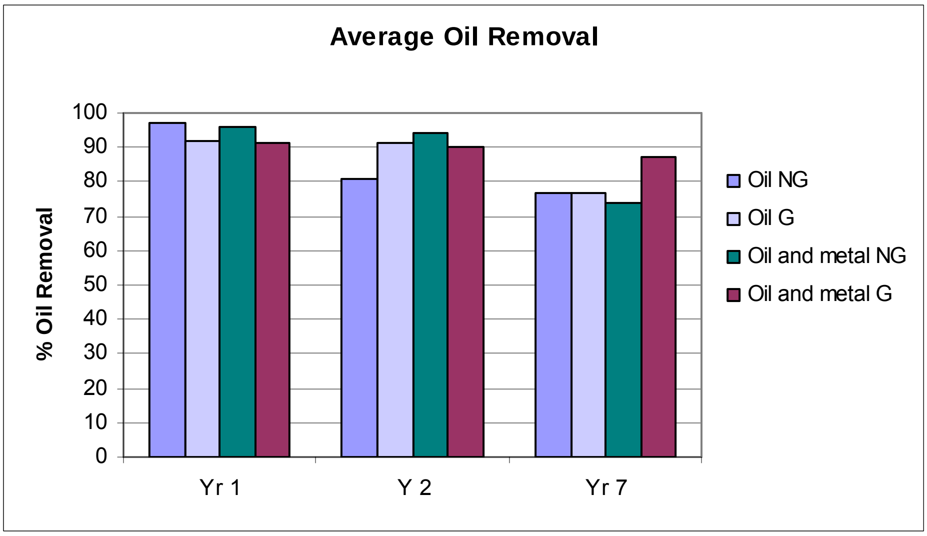
Copper Removal
% Removal
100
90
80
70
60
50
40
30
20
10
0
YR 1
YR 2
YR 7
Metal NG
Metal G
Metal and Oil NG
Metal and Oil G



Lead Removal
% Removal
100
90
80
70
60
50
40
30
20
10
0
YR 1
YR 2
YR 7
Metal NG
Metal G
Metal and Oil NG
Metal and Oil G


Nickel Removal
% Removal
100
90
80
70
60
50
40
30
20
10
0
YR 1
YR 2
YR 7
Metal NG
Metal G
Metal and Oil NG
Metal and Oil G


Zinc Removal
% Removal
100
90
80
70
60
50
40
30
20
10
0
YR 1
YR 2
YR 7
Metal NG
Metal G
Metal and Oil NG
Metal and Oil G


Average Oil Removal
% Oil Removal
100
90
80
70
60
50
40
30
20
10
0
Yr 1
Y 2
Yr 7
Oil NG
Oil G
Oil and metal NG
Oil and metal G

4.5 Metals

The following section addresses in detail the removal of metals in the four test rigs. Removal of metals was consistently greater than 80% apart from in year 1. A lower result in year 1 is intuitively inconsistent and it is likely that a measurement or sampling error occurred.

A very marginally greater removal (2% greater) of metals in the rigs with geotextile may be observed. However, this is no significantly different taking into account the measurement error and a statistical analysis has not been undertaken.

Cadmium percentage removal was greatest in Rig 1, similar to Rig 8. All removed more then 80% of the cadmium in year 1 application. In year 2 both the rigs with only metals applied removed the greatest percentage of the cadmium applied. In Rigs 7 & 8 a greater percentage was removed. After the application of 7 years (total of 10 years) of metal concentration the metal and oil rig with the geotextile removed the greatest percentage of cadmium. The geotextiles test rigs performed best in both pairs of test rigs.

All the test rigs had poor copper removal in year 1, with the oil and metal rigs removing less than 30%. In year two all test rigs removed close to 80%. The non-geotextile metal only rig (Rig 1) removed the greatest percentage overall, with Rig 8 removing more than the metal only test rig with a geotextile. In year 7 all test rigs removed above 80%. Out of both pairs of the test rigs the rigs with the geotextile performed best.

Lead removal was 90% in the geotextile metal and oil test rig and was the best performing in year 1. Rig 1 removed more than the corresponding rig with a geotextile, which was close to the level in Rig 7. In year 2, again, the metal and oil geotextile rig removed the most lead. The geotextile metal only rig removed slightly more than the non-geotextile, both geotextile test rigs therefore performed best. In year 7 both geotextile test rigs preformed best, removing around 95% of lead. The non-geotextile metal only box removed slightly more than the non-geotextile metal and oil test rig.

In year 1 Rig 1 and Rig 7 removed similar amounts of nickel as did the other two test rigs. All removed around 70% in year 2, the metal and oil test rig with a geotextile performed best with 91% removal, with the metal only rigs having very close results. In year 7 all boxes removed more than 90% of nickel, with the non-geotextile metal and oil rig removing the most. The geotextile metal only test rig removed more than the non geotextile test rig.

The metal only non-geotextile rig removed more zinc than the other test rigs. Rig 8 removed a greater percentage than the non-geotextile. In year 2 all test rigs removed more than 80% zinc. Both the test rigs with a geotextile removed the greatest percentage compared to the corresponding test rigs. In year 7 both the geotextile rigs removed a greater percentage than the corresponding non-geotextile.

4.6 Oils

In year 1 all the test rigs removed 90% of the oil applied. Both the test rigs without a geotextile (Rigs 1 & 7) removed a slightly greater percentage. In year 2 the oil only rig with a geotextile removed the greatest percentage with the non-geotextile rig removing slightly more than the geotextile rig in the metal and oil rig. After 7 years of oil application (total 10 years) Rig 8 with a geotextile removed approximately 18% greater than the other test rigs. In contrast, there was no difference in the percentage removal of oil in the two oil only rigs (Rigs 7 & 8). From the results, there is no clear evidence that the presence of geotextile had any impact on the removal of oils.

For all the test results the greatest amount of TPH (total petroleum hydrocarbons) was in the C24-C40 band.

4.7 pH

The ph from all the test runs increased from the ph within the water tank before application. In most case it rose from around 6.5-7 up to 9-9.6. In the metal testing test rigs the ph slowly decreased from year 1 to year 7. This was also evident in the results from the oil test rig without a geotextile. There was a slight increase in the ph levels in the control test rigs, rising from 7.3 to approximately 9 after the run. In the metal and oil test rigs the ph from the tank was 6.9 to 7.5. Increase after the run from 8.2-9.4. The test rig with the geotextile was slightly higher than the non geotextile test rig.

4.8 Suspended Solids

The control and metal test rigs suspended solids levels dramatically decreased from year 1 analysis to year 7, the initial tank reading was 5 whereas the levels from year 1 sample exceeded 500mg/l and year 2 and 7 were above 100mg/l. For the test units containing oil the year 7 suspended solids level slightly increased compared to year 2 results.

5 Discussion of Results

All test rigs had high metal removal rates after 7 years of application with all rigs showing removal rates between 75-95%. Similar results were seen after 2 years of metal application. Results from year 1 show more variability with metal removal percentages 70-95% for nickel, lead, cadmium and zinc. The removal of copper was in the range 25-50% in year 1 but this is considered to be an anomalous set of readings.

Test rigs with a geotextile performed best after the application of 7 years of metals. The results for nickel removal were similar for non-geotextile rigs and rigs with a geotextile, with all removing close to 90%. Year 2 results showed a higher removal rate in test rigs with a geotextile for cadmium, lead and zinc. Again, results after 1 year of metals applied were mixed, with the metal and oil geotextile test rigs removing the highest percentage of metals, whereas metal-only geotextile test rigs removed less than the non-geotextile rig.

Oil removal was greatest in the test rigs with a geotextile after 7 years of application. In the oil-only test rig after 2 years of simulation the geotextile test rig removed a greater concentration of oil. The oil and metal test rig with a geotextile removed slightly less than the non-geotextile test rig with results similar to that of the oil only geotextile test rig. It is concluded that the presence of geotextile had little impact on the removal of oil from the water applied.

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Appendix A
Paving Block Pattern

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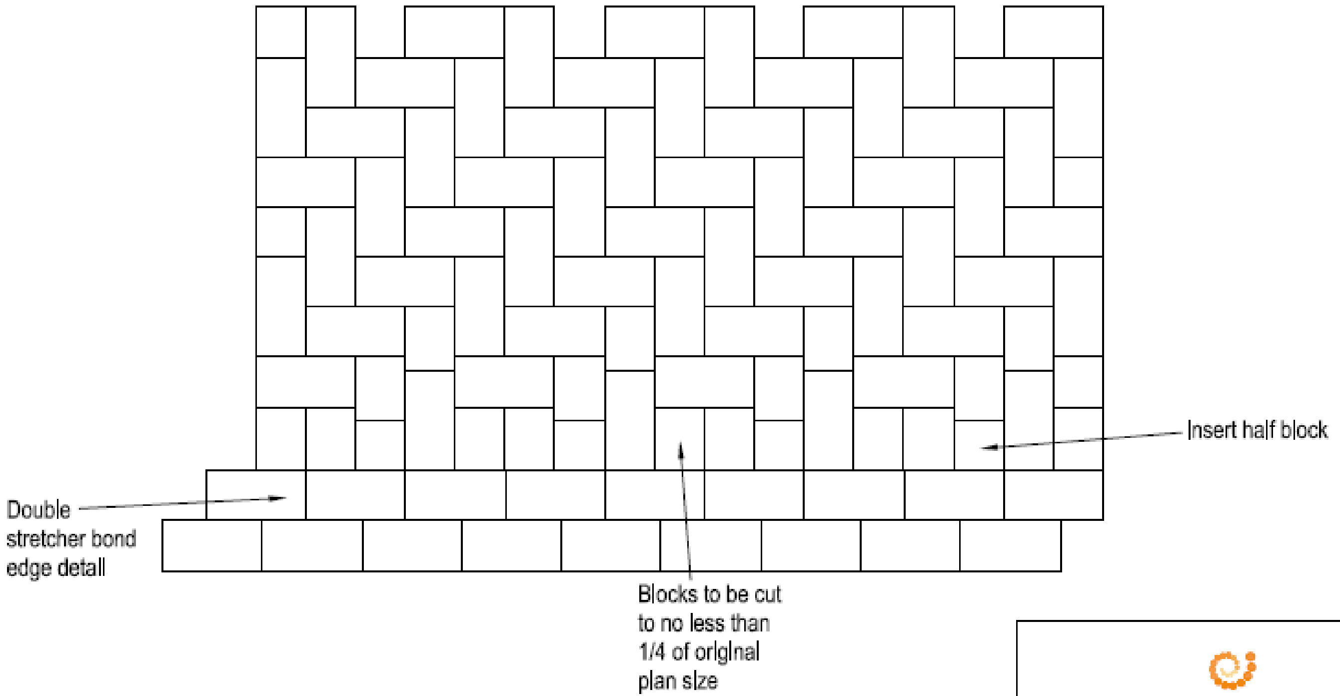

Inboard cutting - 90° herringbone

Note. This drawing to be read in conjunction with the appropriate British Standard or Marshalls Installation Specification. For use with Marshalls products only.

Marshalls
Customer Services, Marshalls PLC,
Landscape House, Premier Way, Lowfields Business Park, Elland, Halifax, HX5 9HT.
Tel: 0870 4113344, Fax: 01422 312943

DRAWING	Inboard Cutting - 90° Herringbone			
DRAWN	SCALE	DATE	Standard No.	REV.
Ian Bull	N.T.S	29/11/01	TS-0204	-

Appendix B
Laboratory Results

Analyte	Units	BOX 1 Yr1 Tank	BOX 1 Yr1 Sample 1	BOX 1 Yr1 Sample 2	BOX 1 Yr1 Sample 3	Box 1 Yr 2 Tank	Box 1 Yr 2 Sample 1	Box 1 Yr 2 Sample 2	Box 1 Yr 2 Sample 3	Box 1 Yr 7 Tank	Box 1 Yr 7 Sample 1	Box 1 Yr 7 Sample 2	Box 1 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	51.4	2.7	2.8	2.9	81.5	3.5	3.4	3.5	176	18.5	19.5	20.9
Copper , Total as Cu	ug/l	123	17	29	29	202	21	20	20	416	60	64	65
Lead , Total as Pb	ug/l	1880	110	114	107	2360	146	137	139	5160	395	416	434
Nickel , Total as Ni	ug/l	639	40	44	42	820	60	59	58	1890	213	228	237
Zinc , Total as Zn	ug/l	2000	157	159	162	3350	244	219	217	6510	908	951	977
pH		6.8	9.1	9	9.1	6.9	8.6	8.8	8.7	6.6	7.6	7.5	7.6
Conductivity- Electrical 20C	uS/cm	112	168	167	160	113	149	150	149	125	154	154	155
Ammoniacal Nitrogen as N	mg/l	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Suspended Solids	mg/l	1	160	167	148	3	90	82	62	1	59	55	58

Analyte	Units	BOX 2 Yr1 tank	BOX 2 Yr1 Sample 1	BOX 2 Yr1 Sample 2	BOX 2 Yr1 Sample 3	Box 2 Yr 2 Tank	Box 2 Yr 2 Sample 1	Box 2 Yr 2 Sample 2	Box 2 Yr 2 Sample 3	Box 2 Yr 7 Tank	Box 2 Yr 7 Sample 1	Box 2 Yr 7 Sample 2	Box 2 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	26.5	4.6	4.5	4.6	58.2	2.5	2.9	3.2	193	14.7	15.4	14.3
Copper , Total as Cu	ug/l	60	29	30	42	136	19	21	38	430	59	50	56
Lead , Total as Pb	ug/l	920	181	189	191	2270	105	117	136	7500	307	294	299
Nickel , Total as Ni	ug/l	315	85	87	91	786	48	47	87	2340	169	163	167
Zinc , Total as Zn	ug/l	988	311	308	319	2210	160	174	263	7240	707	635	660
pH		7.4	9.6	9.6	9.6	6.9	9.1	9.2	9.2	6.2	7.6	7.6	7.6
Conductivity- Electrical 20C	uS/cm	95	198	198	198	112	179	182	180	136	172	171	173
Ammoniacal Nitrogen as N	mg/l	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Suspended Solids	mg/l	1	554	562	582	2	114	112	121	2	65	66	61

Analyte	Units	BOX 3 Yr1 Tank	BOX 3 Yr1 Sample 1	BOX 3 Yr1 Sample 2	BOX 3 Yr1 Sample 3	Box 3 Yr 2 Tank	Box 3 Yr 2 Sample 1	Box 3 Yr 2 Sample 2	Box 3 Yr 2 Sample 3	Box 3 Yr 7 Tank	Box 3 Yr 7 Sample 1	Box 3 Yr 7 Sample 2	Box 3 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	0.8	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	0.8	1	0.7
Copper , Total as Cu	ug/l	<1	23	28	11	1	4	5	5	2	15	14	13
Lead , Total as Pb	ug/l	<5.0	<5.0	<5.0	5.1	<5.0	<5.0	<5.0	7	7.2	12.6	18.7	15
Nickel , Total as Ni	ug/l	<2	27	24	27	<2	11	17	12	<2	<2	<2	<2
Zinc , Total as Zn	ug/l	15	82	62	79	4	41	32	45	37	81	103	90
pH		7.8	9.4	9.3	9.3	7.9	9	9.1	8.7	7.4	8.8	8.5	8.7
Conductivity- Electrical 20C	uS/cm	87	141	144	142	96	138	130	135	89	124	130	128
Ammoniacal Nitrogen as N	mg/l	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Suspended Solids	mg/l	4	322	326	316	1	223	62	253	2	291	296	298
TPH >C6-C40	ug/l	N/S	<20	22	<20	N/S	265	163	188	N/S	1000	906	627
TPH >C6-C8	ug/l	N/S	<20	<20	<20	N/S	<10	<10	<10	N/S	<10	<10	<10
TPH >C8-C10	ug/l	N/S	<20	<20	<20	N/S	<10	<10	<10	N/S	<10	<10	<10
TPH >C16-C24	ug/l	N/S	<20	<20	<20	N/S	20	13	14	N/S	96	86	66
TPH >C24-C40	ug/l	N/S	<20	22	<20	N/S	245	150	174	N/S	908	820	561
TPH >C10-C16	ug/l	N/S	<20	<20	<20	N/S	<10	<10	<10	N/S	<10	<10	<10

Analyte	Units	BOX 4 Yr1 Oils Tank	BOX 4 Yr1 Sample 1	BOX 4 Yr1 Sample 2	BOX 4 Yr1 Sample 3	Box 4 Yr 2 Tank	Box 4 Yr 2 Sample 1	Box 4 Yr 2 Sample 2	Box 4 Yr 2 Sample 3	Box 4 Yr 7 Tank	Box 4 Yr 7 Sample 1	Box 4 Yr 7 Sample 2	Box 4 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	<0.6	47.1	N/S		<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	0.9	1
Copper , Total as Cu	ug/l	<1	86	N/S		1	4	6	5	2	12	12	13
Lead , Total as Pb	ug/l	<5.0	130	N/S		<5.0	<5.0	<5.0	<5.0	10.6	11	9.6	15
Nickel , Total as Ni	ug/l	<2	61	N/S		<2	8	9	9	<2	<2	<2	<2
Zinc , Total as Zn	ug/l	<3	1020	N/S		9	32	40	39	<3	58	109	65
pH		7.9	7.6	N/S		7.8	9.3	9.3	9.2	7.8	8.5	8.3	8.4
Conductivity- Electrical 20C	uS/cm	86	216	N/S		97	148	144	147	90	122	121	125
Ammoniacal Nitrogen as N	mg/l	<0.19	0.59	N/S		<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	N/S		<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Suspended Solids	mg/l	1	1010	N/S		4	233	125	120	2	208	199	198
TPH >C6-C40	ug/l	N/S	<20	70		<10	91	73	125	N/S	888	979	839
TPH >C6-C8	ug/l	N/S	<20	<40		<10	<10	<10	<10	N/S	<10	<10	<10
TPH >C8-C10	ug/l	N/S	<20	<40		<10	<10	<10	<10	N/S	<10	<10	<10
TPH >C16-C24	ug/l	N/S	<20	<40		<10	<10	<10	12	N/S	96	98	95
TPH >C24-C40	ug/l	N/S	<20	70		<10	91	73	113	N/S	792	882	744
TPH >C10-C16	ug/l	N/S	<20	<40		<10	<10	<10	<10	N/S	<10	<10	<10

Analyte	Units	BOX 5 Yr1 Oils Tank	BOX 5 Yr1 Sample 1	BOX 5 Yr1 Sample 2	BOX 5 Yr1 Sample 3	Box 5 Yr 2 Tank	Box 5 Yr 2 Sample 1	Box 5 Yr 2 Sample 2	Box 5 Yr 2 Sample 3	Box 5 Yr 7 Tank	Box 5 Yr 7 Sample 1	Box 5 Yr 7 Sample 2	Box 5 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	0.7	0.8	0.8	0.9
Copper , Total as Cu	ug/l	3	9	11	8	<1	20	6	5	2	13	17	18
Lead , Total as Pb	ug/l	<5.0	<5.0	<5.0	<5.0	<5.0	9.6	5.1	<5.0	9	13.3	11	14.9
Nickel , Total as Ni	ug/l	<2	24	26	19	6	25	10	11	<2	<2	<2	<2
Zinc , Total as Zn	ug/l	9	52	108	43	8	137	31	33	<3	40	41	34
pH		7.7	9.3	9.2	9.3	7.7	9	9	9.1	7.6	8.9	8.9	8.9
Conductivity- Electrical 20C	uS/cm	102	153	157	155	99	142	142	148	88	125	125	126
Ammoniacal Nitrogen as N	mg/l	0.47	<0.19	0.23	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08
Suspended Solids	mg/l	6	192	210	188	5	171	161	162	3	101	96	97

Analyte	Units	BOX 6 Yr1 Oils Tank	BOX 6 Yr1 Sample 1	BOX 6 Yr1 Sample 2	BOX 6 Yr1 Sample 3	Box 6 Yr 2 Tank	Box 6 Yr 2 Sample 1	Box 6 Yr 2 Sample 2	Box 6 Yr 2 Sample 3	Box 6 Yr 7 Tank	Box 6 Yr 7 Sample 1	Box 6 Yr 7 Sample 2	Box 6 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	0.8	1.2	0.9	<0.6
Copper , Total as Cu	ug/l	2	5	5	4	<1	6	5	6	2	13	17	16
Lead , Total as Pb	ug/l	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	9	11	8.5	11.5
Nickel , Total as Ni	ug/l	<2	10	9	9	<2	6	4	6	<2	<2	<2	<2
Zinc , Total as Zn	ug/l	4	23	24	23	<3	16	16	18	6	24	27	23
pH		7.9	9.3	9.3	9.3	7.9	9	9	8.9	7.6	8.6	8.5	8.5
Conductivity- Electrical 20C	uS/cm	86	136	137	137	99	142	139	139	90	120	121	121
Ammoniacal Nitrogen as N	mg/l	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	1.13	0.96	0.75	0.61
Suspended Solids	mg/l	1	124	107	125	1	93	92	116	3	62	67	70

Analyte	Units	BOX 7 Yr1 Oils Tank	BOX 7 Yr1 Sample 1	BOX 7 Yr1 Sample 2	BOX 7 Yr1 Sample 3	Box 7 Yr 2 Tank	Box 7 Yr 2 Sample 1	Box 7 Yr 2 Sample 2	Box 7 Yr 2 Sample 3	Box 7 Yr 7 Tank	Box 7 Yr 7 Sample 1	Box 7 Yr 7 Sample 2	Box 7 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	20.5	3.7	4.1	3.7	55.8	6	6.2	5.2	82.1	12.1	13.6	11.6
Copper , Total as Cu	ug/l	41	40	43	39	137	39	21	17	398	71	76	78
Lead , Total as Pb	ug/l	612	151	177	166	2030	195	205	167	6510	546	595	561
Nickel , Total as Ni	ug/l	228	77	87	83	673	97	101	81	2950	289	312	302
Zinc , Total as Zn	ug/l	716	245	277	263	2210	339	337	267	10400	1120	1190	1170
pH		7.5	9.2	9.2	9.3	7.1	8.4	8.5	8.5	6.7	7.8	7.7	7.7
Conductivity- Electrical 20C	uS/cm	92	152	151	151	110	150	147	150	137	152	152	153
Ammoniacal Nitrogen as N	mg/l	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	0.45	<0.08	<0.08	<0.08
Suspended Solids	mg/l	2	448	512	512	3	136	121	174	15	207	175	185
TPH >C6-C40	ug/l	N/S	21	31	<20	<10	74	59	71	N/S	825	956	778
TPH >C6-C8	ug/l	N/S	<10	<20	<20	<10	<10	<10	<10	N/S	<10	<10	<10
TPH >C8-C10	ug/l	N/S	<10	<20	<20	<10	<10	<10	<10	N/S	<10	<10	<10
TPH >C16-C24	ug/l	N/S	<10	<20	<20	<10	<10	<10	<10	N/S	95	103	82
TPH >C24-C40	ug/l	N/S	21	31	<20	<10	74	59	71	N/S	718	853	683
TPH >C10-C16	ug/l	N/S	<10	<20	<20	<10	<10	<10	<10	N/S	13	<10	13

Analyte	Units	BOX 8 Yr1 Oils Tank	BOX 8 Yr1 Sample 1	BOX 8 Yr1 Sample 2	BOX 8 Yr1 Sample 3	Box 8 Yr 2 Tank	Box 8 Yr 2 Sample 1	Box 8 Yr 2 Sample 2	Box 8 Yr 2 Sample 3	Box 8 Yr 7 Tank	Box 8 Yr 7 Sample 1	Box 8 Yr 7 Sample 2	Box 8 Yr 7 Sample 3
Cadmium , Total as Cd	ug/l	24.2	2.8	2.6	2.4	33.7	3.6	3.3	4.8	22.9	3.2	4.3	3.4
Copper , Total as Cu	ug/l	57	22	30	20	83	16	16	39	320	72	59	70
Lead , Total as Pb	ug/l	799	81.1	72.3	85.7	<5	80	83.3	78.5	5210	368	322	348
Nickel , Total as Ni	ug/l	277	43	45	45	404	43	45	45	1840	198	166	189
Zinc , Total as Zn	ug/l	1060	162	178	329	1390	180	184	251	6440	805	670	761
pH		7.2	9.4	9.4	9.4	6.9	9	8.3	8.9	6.9	8.4	8.1	8.1
Conductivity- Electrical 20C	uS/cm	92	156	156	157	103	152	154	155	122	164	163	163
Ammoniacal Nitrogen as N	mg/l	<0.19	0.2	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19	<0.19
Phosphate, Ortho as P	mg/l	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	0.33	0.29	0.23
Suspended Solids	mg/l	1	406	432	420	3	165	198	189	2	236	251	239
TPH >C6-C40	ug/l	N/S	46	51	49	<10	96	107	130	N/S	262	489	577
TPH >C6-C8	ug/l	N/S	<20	<20	<20	<10	<10	<10	<10	N/S	<10	<10	<10
TPH >C8-C10	ug/l	N/S	<20	<20	<20	<10	<10	<10	<10	N/S	<10	<10	<10
TPH >C16-C24	ug/l	N/S	<20	<20	<20	<10	<10	<10	12	N/S	37	56	64
TPH >C24-C40	ug/l	N/S	46	51	49	<10	96	107	118	N/S	226	433	514
TPH >C10-C16	ug/l	N/S	<20	<20	<20	<10	<10	<10	<10	N/S	<10	<10	<10

Appendix C
Literature Review

Literature Review of permeable paving systems with or without an upper geotextile membrane for Marshalls

Authors

J. Mullaney Ma

L. Samson BSc

C. Jefferies BSc, MSc, PhD

Contents

1. Executive Summary

A literature review of geotextiles in permeable pavements was undertaken. Some 63 papers were reviewed. These were primarily written in English, although some papers in French and German were also reviewed. No studies were found which directly compared tests which included geotextiles with those which did not.

It is concluded that there is no evidence to support the view that a geotextile layer is required on the grounds of pollutant removal and that a test programme to enable this comparison will be valuable. A test set up is recommended.

2. Introduction

Permeable pavement systems within the UK have become a popular solution in reducing the burden of increased runoff on urban waterways due to the continuing expansion of urban and industrial areas. The change from permeable land to urban or industrial areas increases impermeable surfaces such as roofs, roads and pavements, thus reducing groundwater recharge and creating a larger volume of runoff and higher peak flow rates in the drainage system. During heavy rainfall when the sewers are at capacity, this can often lead to urban flooding.

The runoff from urban areas carries various pollutants including heavy metals, oils other hydrocarbons and suspended solids which have been deposited onto impermeable surfaces. "The majority of pollution in urban stormwater originates from non-point or diffuse sources" (Pratt et al, 1999). They are often difficult to locate and can come from a variety of sources including traffic emissions, decomposing litter, salts, soil losses etc. These pollutants pose a risk to the watercourse quality and to the soil if they remain untreated.

Permeable pavements help to restore the infiltration and hydraulic functions to urban areas and to increase water quality. They are constructed using various permeable surfaces: porous asphalt, porous concrete, plastic grid systems and permeable pavers. Water infiltrates through voids in the surface into the bedding layer and the high void aggregate sub base below; which acts as a temporary storage area until the water percolates into the soil or is drained to a stormwater channel.

Geotextile membranes may be present at two levels within the permeable paving structure. At the upper level the permeable geotextile separates the bedding layer and sub base, while at the lower level the impermeable membrane separates the sub base from the sub grade. Geotextiles at either level are currently incorporated by all of the reviewed manufacturers in line with British Standards (and US equivalent standards) and site specific conditions. However, there is a growing debate about benefits achieved by an upper geotextile, primarily from a water quality point of view.

A large number of studies have been conducted on the pollution removal efficiency of permeable pavements, their hydraulic properties and the effect of clogging. The overall objective of this literature review was to determine whether there was evidence to suggest the upper geotextile is required for water quality or other benefits within the permeable paving system. Suitable experimental procedures for the evaluation of an upper geotextile layer within Marshalls Priora paving system would also result from the review.

The review had three objectives:

1. Conduct a review of experimental procedures carried out on permeable paving systems and the various laboratory rig designs used.

2. To determine the types of pollutants which have been investigated, how/if the pavement retains them and how/if are they affected by the presence of an upper geotextile

3. To determine what the hydraulic properties of permeable pavements are and how/if they are affected by geotextiles.

3. Review of Information in the Literature

This topic has a wide range of literature available dealing with a number of issues including pollution retention, hydraulic properties, oil breakdown and clogging effects.

A large number of research papers have been produced by Coventry University under the direction of C.J Pratt and A.P Newman, particularly on oil breakdown within a permeable paving structure. North Carolina University has been more focused on the hydraulic properties within the structure and W.F Hunt and E.Z Bean have both produced numerous papers from research sites within North Carolina. Work in Germany has tended to focus on the pollution retention capacity of permeable paving, authors such as C Dierkes. Studies have also been carried out across America by U.S Environment Protection Agency and Virginia State Polytechnic as well as the University of Guelph in Canada which has a large research facility.

Due to the wide variety of literature available, this section has been divided into experimental procedures, pollutants and hydraulic studies. The papers discussed, along with others can be seen in Table 1, Table 2 and Table 3. Table 1 is an overview of the literature, stating author, article and publication. Table 2 contains the various pollutants applied to the structure i.e. metals, oils, with details of the concentrations applied and the percentage retained within the structure. Table 3 refers to the current geotextiles used by permeable paving manufacturers, discussing any comments made by the manufacturer on pollution retention or hydraulic properties.

Table 1. Articles Reviewed

Art. No	Author	Year	Article	Publication
1	Acheson & Glover Ltd	**2009**	EnviroPerm Permeable Paving Solutions	www.bpindex.co.uk
2	Anderson, C.T, Foster, I.D.L and Pratt, C.J	1999	The role of urban surfaces in regulating drainage and evaporation: deveolpment of a lab simulation experiment	Hydraulic processes, 13, 597-609
3	Balades, J.D, Legret, M and Madiec, H	1995	Permeable pavements: pollution management tools	Water science and technology, 32, 1, 49-56
4	Barraud, S., Gautier, A., Bardin, J.P. And Riou, V.	1999	The impact of intentional stormwater infiltration on soil and groundwater	Water science and technology, 39, 2, 185-192
5	Barrett, M.E., Kearfott, P. And Malina Jr, J.F.	2006	Stormwater Quality Benenfits of a Porous Friction Course and its Effect on Pollutant Removal by Roadside Shoulders	Water Environment Research, 78, 11, 2177-2185
6	Bean, E.Z, Hunt, W.F Bidelspach, D.A and Burak, R.J	2004	Study on the surface infiltration rate of permeable pavements	1st Water and Environmental Specialty Conference of the Canadian Society for Civil Eng.
7	Bean, E.Z, Hunt, W.F, and Biedelspach, D.A	2004	A monitoring field study of permeable pavement sites in North Carolina	www.bae.ncsu.edu/info/permeable-pavements
8	Berbee, R, Rijs, G, de Brouwer, R and van Velzen, L	1999	Characterization and treatment of runoff from highways in the Netherlands with impervious and pervious asphalt	Water Environment Research; 1999; 71, 2, 183-190
9	Borgwardt, S.	2006	Long-term in-situ infiltration performance of permeable concrete block pavement	8th International Conference on Concrete Block Paving
10	Bouteligier, et. al.	2007	The permeable paving experiment test site at the Belgian Road Research Centre	Novatech, 2007
11	Bowyer-Bower, T.A.S and Burt, T.P	1989	Rainfall simulators for investigating oil repsonse to rainfall	Soil Technology, 2, 1-16
12	Brattebo, B.O, and Booth, D.B	2003	Long term stormwater quantity and quality performance of permeable pavement systems	Water Research, 37, 4369-4376
13	Brett Landscaping		Permeable Paving & Brett Flow	www.brett.co.uk
14	Burak, R	2007	Construction of bases for permeable interlocking concrete pavements-art 1	Interlocking concrete pavement magazine
15	Charcon		Permafilter geotextile, Infilte Block Paving Info	www.aggregate.com
16	Collins, K.A, Hunt, W.F, and Hathaway, J.M	2006	Evaluation of various types of permeable pavements with respect to water quality improvement and flood control	8th International Conference on Concrete Block Paving
17	Collins, K.A, Hunt, W.F, and Hathaway, J.M	2008	Hydraulic and water quality evaluation of four permeable pavements in North Carolina, USA	11th ICUD , Edinburgh
18	Davis, P.A, Shokouhian, M and Ni, S	2000	Loading estimates of lead, copper, cadmium and zinc in urban runoff from specific sources	Chemosphere, 44
19	Day, G.E, Smith, D.R and Bowers, J	1981	Runoff and pollution abatement characteristics of concrete grid pavements	Virginia Polytechnic Intitute and State University research project
20	Dierkes, C, Lohmann, M, Becker, m and Rassch, U	2005	Pollution retention of different permeable pavements with reservoir structure at high hydraulic loads	10th ICUD, Copenhagen
21	Dierkes, et. Al.	2001	Pollution retention capability and maintenance of permeable pavements	In: Strecker, E.W, editor, Proceedings of the 9th ICUD
22	Dierkes, C, Gobel, ., Benze, W and Wells, J	2002	Next Generation Water sensitive Stormwater Management Techniques	2nd National Conference on Water Sensitive Urban Design
23	Dierkes, C, Holte, A and Geiger, W.F	1999	Heavy metal retention within a porous pavement structure	8th ICUD
24	USEPA	1999	Storm Water Technology (SWT) Fact Sheet: Porous Pavement	www.epa.gov
25	USEPA	2000	SWT Fact Sheet: Porous Pavement	www.epa.gov
26	USEPA	2001	SWT Fact Sheet: Porous Pavement	www.epa.gov
27	USEPA	2002	SWT Fact Sheet: Porous Pavement	www.epa.gov
28	USEPA	2003	SWT Fact Sheet: Porous Pavement	www.epa.gov
29	USEPA	2004	SWT Fact Sheet: Porous Pavement	www.epa.gov
30	USEPA	2005	SWT Fact Sheet: Porous Pavement	www.epa.gov
31	Hanson Heidelberg Cement Group		Formpave	www.heidelbergcement.com
32	Hunt, W.F and collins, K	2007	Urban waterways-permeable pavements-research update and design implications	Department of biological and agricultural engineering
33	Hunt, W.F and Stevens, S	2001	Permeable pavement use and research at Hannibal Parking lots at Kingston, NC	Water quality group newsletter
34	Hunt, W.F, Stevens, S and Mayes, D	2002	Permeable pavement use and research at two stes in easten North Carolina	9th ICUD, Portland , USA

35	Hydropave		Hydropave Permeable Paving	www.tobermore.co.uk
36	Interpave	2005	Guide to the design construction and maintenance of concrete block permeable pavements	www. Paving.org.uk
37	James, W And Thompson, M.K	1997	Contaminants from four new pervious and impervious pavements in a parking lot	Advances in Modelling the Management of Stormwater Impacts, Vol 5, Ch 11 207-222
38	Jayasuriya, N and Kadurupokune, N	2008	Impact of pervious pavements on drainage infrsstructure	11th ICUD, Edinburgh
39	Knapton, J, Cook, I and Morell, D	2002	A new design method for permeable pavements surfaces with pavers	Journal of the Institution of Highways and Transportation
40	Legret, M, Colandini, V and Le Marc, C.	1996	Effects of a porous pavement with reserviour structure on the quality of runoff water and soil	The Science of the Total Environment 189/190 (1996) 335-340
41	Marshalls Plc		Priora Permeable Paving Design Guide	www.marshalls.co.uk
42	Neary, V.S, Neel, T.C and Dewey, J.B	2002	Pollutant washoff and loading from parking lots in Cooksville Tennessee	9th ICUD Portland, USA
43	Newman, A.P et. Al	2001	Oil retention and microbial ecology in porous pavement structures	European forum of env. research laboratories, Rennes, France
44	Newman, A.P and Pratt, C.J, Coupe, S.J and Cresswell, N	2002	Oil bio-degredation in permeable pavements by microbial communitites	Water science and technology, 45, 7, 51-56
45	Newman, A.P, et. al	2002	Microbial ecology of oil degrading porous pavement structures	9th ICUD Portland, USA
46	Newman et. Al.	2004	Protecting groundwater with oil-retaining pervious pavements: historical perspectives, limitations and recent developments	Quarterly Journal of Eng. Geology and Hydrogeology, 37, 283-291
47	Portland Government	2003	Sustainable Infrastructure Alternative Paving Materials Subcommittee Review	Portland Government Research study
48	Pratt, C.J, Mantle, D.G, and Schofield, P.A	1995	UK research into the performance of permeable pavement, reservior structures in controlling storwater discharge quantity and quality	Water science and technology, 32, 1, 63-69
49	Pratt, C.J	1997	Design guidelines for porous/permeable pavements	Sustaining urban water resources in the 21st century conference
50	Pratt, C.J, Newman, A.P and Bond, P.C	1999	Mineral oil bio-degradation within a permeable pavement: long term observations	Water science and technology, 39,2, 103-109
51	Puehmeier, T and Newman, A.P	2008	Oil retention and treating geotextile for pavement applications	11th ICUD, Edinburgh
52	Rankin, K. And Ball, J.E.	2004	A review of the performance of permeable pavers	The University of South Wales
53	Revitt, D.M, Garelick, H and Worrall, P	2002	Pollutant biodegradation potentials on airport surfaces	9th ICUD, Portland, USA
54	Rowe, A.A, Borst, M and O'Connor, T.P	2008	Pervious pavement system evaluation	Proceedings of the World Environmental and Water Research Congress, 2009
55	Scholz, M and Grabowiecki, P	2007	Review of permeable pavement systems	Building and Environment, 42, 3830-3836
56	Seneca College	2007	Performance Evaluation of permeable pavement and bioretention swale	Toronto and Region Conservation Interim Report 3
57	Straet, F, Beckers, E and Degre, A.	2008	Hydraulic behaviour of greened porous pavements:a physical study	11th ICUD, Edinburgh
58	Swisher, D	2002	Chemical and hydraulic performance of a porous pavement parking lot with infiltration to ground water	Thesis, The Pennsylvania State University
59	Tarmac Limited	n.d	TarmacDry® technical information and specifications.	www.tarmac.co.uk
60	Uni-group USA	2002	Uni eco-stone guide and research summary	Uni-group USA research summary
61	van Duin, B, Brown, C, Chu, A, Marsalek, J and Valeo, C	2008	Characterization of long-term solids removal and clogging processes in two types of permeable pavement under cold climate conditions	11th ICUD, Edinburgh
62	Wu, Y.S, Allan, C.J, Saunders, W.L and Evett, J.B	1998	Characterization and pollutant loading estimation for highway runoff	Journal of Environmental Engineering, 584-592
63	Yong, C.F, Deletic, A, Fletcher, T.D and Grace, M.R	2008	The clogging behaviour and treatment efficiency of a range of porous pavements	11th ICUD, Edinburgh

Table 2. Pollutants

Art No.	Metals	Oils	Intensity	Percentages retained
3	Pb, Cu, Zn	n/a	n/a	% reduction Pb:65, Cu:48, Zn:56
4	Pb, Cd, Zn,	TOC	n/a	Abatement - Zn:74%, Pb:98.5%
5	Pb, Cu, Zn	n/a	n/a	Reduction %- TSS: 94, TKN:43, Cu:75, Pb: 93, Zn: 76, COD:46
6	Cu and Zn	n/a	n/a	Phosphorus lower in infiltrate than runoff. Storms 2-6 of copper was lower than detectable layer, zinc higher in runoff.
7	Copper, zinc,	n/a	n/a	1:TN not lower, suggests NH_4N- and TKN converted by ammonification and nitrification. 2:higher in runoff than exfiltrate.
8	Cu, Cr, Cd, Ni, Zn, Pb	Oil, PAH	Natural rain and highway runoff amounts not controlled	Concentrations of pollutants in runoff are significantly lower in pervious asphalt in comparison to impervous asphalt
12	zinc, copper, lead	diesel fuel, motor oil	all samples below minimum detection level.	See section 3.1 of Literature review
16	n/a	n/a	n/a	All pavements retained a greater percentage of pollutants in comparison to asphalt
17	Cu, Zn	n/a	n/a	All pavements retained a greater percentage of pollutants in comparison to asphalt
19	Pb, Zn, Ch	TOC	n/a	several tables to show pollutant % retained
20	Pb, Cu, Zn, Cd	n/a	n/a	See section 3.1 of Literature review
21	lead, cadmium, copper, zinc	n/a	n/a	See section 3.1 of Literature review
22	cadmium, copper, lead, nickel, chromium	n/a	n/a	n/a
23	Pb, Cu, Zn, Cd	n/a	n/a	Pb: 98%, Cd:74-98%, Cu: 96 - 89%, Zn: 97-72 dependent on sub-base
24	(TN), (NO3-N), (TKN), (NH4-N), (ON), (TP), (PO4), (BP), (Zn), (Cu), (TSS) .	n/a	n/a	All permeable pavement sections appear to cause substantial reductions in surface runoff volume. These reductions may be dependant on type of pavement or pavement fill.
26	Zn, Cu, and Pb	n/a	n/a	The road construction with the brick-filled infilinfiltration pores had a pollutant retention efficiency of 99.2%, that with the basalt filled infiltration pores had 99.0%
27	Zn, Cu, and Pb	PAHs	Results found in runoff 1.3-3.3µg/L	
29	copper, lead, zinc	n/a	n/a	See section 3.1 of Literature Review
32	n/a	n/a	n/a	Most heavy metals are captured in the top layers (1 to 2 in) of material in permeable pavement void space
37	copper, nickel, zinc, cadmium, chromium, lead, iron	solvent extractable oils and grease	not stated	cadmium, lead, chromium, copper, nickle were all highest in CP paving structure. Zinc and irn were highest in the AS structure with ammonia being highest within the Cp structure and the other structure being similar to one another.

40	Pb, Zn, Cu, Cd	total hydrocarbons	natural pollutant levels	significant increase in metal content on the geotextile layer, lead predominantly found between 60 and 75 cm below the surface. Contents of all pollutants tested was much lower further down the structure.
42		PAHs	natural application	Flow rate varied with highest being 16l/s
43	n/a	oil, applied to 310 x310mm area of paving.	320µl over the entire study per structure. Started at 8ml per oil application then upto 20ml.	99.6% oil and grease retained of the initial volume applied. Asphalt 49.6% and concrete 70.8%
44	n/a	oil	See section 3.3 of literature review	large rig was 99% efficiency in terms of oil retention. Both sets of medium rigs, innoculated and non innoculated had 99% retention.
45	n/a	n/a	n/a	After 4 years the permeable pavementstructure continues to retain over 99% of added oil and shows good evidence of continuing microbial activity. This is due to a combination of efficient retention and biological breakdown
46	n/a	oil	oil, applied , 3 x 8ml per 130ml of simulated rainwater	greatest retention of oil with a woven geotextile without silt
48	Pb, Cl	n/a	n/a	Varied with sub base
49	Various	Various	Various	Various
50	n/a	oil and grease	See section 3.3 of literature review	2.4 % applied was not retained within the system, degradation of oil depends on nutrient supply
51	n/a	oil	600ml/m2. six replica tests carried out on new geotextile over 189mins.	n/a
52	Pb, Zn, Fe, Cu, Cd, Cr, Ni, Mn	Petroleum Hydrocarbons, PAH, PCBs	Natural rain and highway runoff amounts not controlled	n/a
53	n/a	Glycols Acetates	Actual airport levels not written	only specifies glycol degradation quantities
56	wide array of metals including cadmium, copper, iron, magnesium, nickel, lead, zinc	n/a	n/a	Suspended solids entering through the surface are trapped in void spaces as they migrate through the soil
58	Ca, Mg, Pb, Zn, Cu, Al, Fe, K, Mn, Na	TOC	Natural rain and highway runoff amounts not controlled	Metals contained in the infiltrating stormwater were removed in the top few inches of the soil.
62	Cu, Cr, Pb, Ni	Oil and grease	Natural rain and highway runoff amounts not controlled	Pollutants in the effluent were monitored and compared to US and German averages - see Wu Pollutants
63	lead, zinc, copper, cadmium.	n/a	n/a	TSS:After 17.5yrs PA 79%, HP94% PP 85%, TP: PA 28% HP 43% PP 33%, TN: PA 16%, HP 29%, PP 23%
	25 papers	18 papers		

Table 3. Geotextile Manufacturers

Art.	Manufacturer	Geotextile Comments	Ass'nt*	Water quality benefits claimed
1	Acheson & Glover Ltd	As part of the site specific design approach, it may be necessary to include geotextiles. In certain circumstances, layers of geogrid may be introduced into the pavement construction to ensure the completed pavement is capable of carrying the design loadings. Geotextiles are used to line the surface of the sub-grade preventing punching of aggregate into the sub-grade. Typically monofilament products manufactured from polypropylene or polyethylene or similar are used, as the geotextile must remain capable of allowing free movement of water whilst dealing with the loadings both during construction and during the pavement lifetime. Specify products to BS EN 13252 :2001.	No	No
13	Brett Landscaping	No information on geotextile use	No	No
15	Charcon	Geotextiles are used in some permeable pavement applications. The Permafilter Geotextile is a non-woven, dimpled, needle punched geotextile that has been specifically designed for hydrocarbon pollution treatment in civil engineering application.	No	Specifically designed for hydrocarbon pollution treatment, the entrapped hydrocarbons can be biodegraded by naturally occurring micro-organisms providing a self-cleansing mechanism. Capable of retaining oil contamination ranging from daily car drip losses up to catastrophic spillages
31	Hanson Heidelberg Cement Group	All oils and silts are captured by the INBITEX Geotextile. It is not clear if Hansons use the inbitex geotextile for each permeable paving construction. 70% polypropylene, 30% polyethylene construction	0.145mm pore size, mean flow 80l/m2.sec	All oils and silts are captured by the INBITEX Geotextile
35	Hydropave	An upper geotextile may be used between the sub-base and the bedding layer. Please refer to BS7533-13:2009 for further information. Tobermore recommends that its Hydropave products be installed in conjunction with a BS EN 7533-13:2009 designed permeable paving system. Sub-base aggregates, Bedding layer aggregates and Jointing aggregates conform to BS EN13242:2002	No	No
41	Marshalls Plc	An upper geotextile may be used between the sub-base and the bedding layer. Please refer to BS7533-13:2009 for further information		
59	Tarmac Limited	For infiltration applications a geotextile is incorporated on top of the prepared sub-grade to provide additional filtration prior to discharge into the underlying layers. The geotextile also stops very fine material present in the sub-grade being pumped upwards into the granular layer which could result in partial blocking and reduced storage capacity	No	The geotextile provides additional filtration prior to discharge into the underlying layers. The geotextile also stops very fine material present in the sub-grade being pumped upwards into the granular layer which could result in partial blocking and reduced storage capacity
60	Uni-group USA	Typical eco-stone construction shows only lower geotextile filter layer. Geotextiles may be used in some PICPs, but are optional when using a No. 2 aggregate subbase. If filter criteria between the layers of the pavement (subgrade, base, and bedding) cannot be maintained with the aggregate materials selected for the project, or if traffic loads or soils require additional structural support, geotextiles may be used.	No	No
		8 Papers/Documents		

*Hydraulic assessment of geotextile

4. Experimental Procedures

Numerous experimental procedures have been used including variations in the following:

- Rig size and design
- Number of rigs used
- Rainfall simulation method

4.1. Rig size and design

The majority of these experiments have been conducted at the laboratory scale but there are several which have been done at larger scales within the field. Studies such as those by Anderson et al (1999) and Rowe et al (2008) where large boxes were constructed to act as a test site have been effective in creating a permeable paving area at a more manageable scale. In the case of Rowe et al (2008) four structures were constructed, 60cm x 60cm x 90cm in plastic bins. Those used in the study by Anderson et al (1999) were the same size and in a study by Pratt et al (1999) boxes of a similar size, 61cm x 61cm x 78cm, were used. Newman et al (2001) used slightly smaller structures within the laboratory, constructing an aluminium box 400mm x 400mm x 600mm. A study by Yong et al (2008) on the effects of clogging within systems used a rig 2.7 x 0.45 x 1.95m, separated into three vertical compartments with a Perspex front which to enable the visibility of ponding.

Four of the above laboratory experiments mentioned all consisted of a similar structural pattern, concrete interlocking blocks lain on a layer of aggregate, the voids filled with sand or crushed gravel, below the aggregate layer was then another layer of larger aggregate, all lying upon a geotextile membrane above the soil. Of the papers looked at there was only a small number which included an upper geotextile layer, those by Newman et al (2001, 2002, 2004) Pratt et al (1995) and Puehmeier and Newman (2008). Rowe et al (2008) was the only known study to be conducted with one rig set up with an upper geotextile and another without.

Another design feature which had to been considered was how the discharge from the porous paving structure would be collected. Rowe et al (2008) for example installed a pipe at the bottom of the structure during construction to collect the discharge, this then exited through the bin wall to allow collection of effluent. This is the design commonly carried out in field studies.

The studies constructed at a much larger scale within the field such as those by Bean et al (2004) and Brattebo and Booth (2003) constructed test sites as they would have been on a normal site. The only difference was that a gutter and pipe system was installed to collect infiltration and runoff. The structural patterns were very similar to those for the laboratory experiment.

4.2. Number of rigs used

The number of laboratory rigs used is study dependant. In some studies only one test rig has been used but in other studies much larger numbers of test sites/rigs have been used. Laboratory rigs have been constructed in most studies at smaller quantities than those in the field. On average four were constructed, with the largest number constructed being 20 by Newman et al (2002). In some studies such as that by Brattebo and Booth (2003), replicas of each rig were constructed to ensure results were more reliable. The number of rigs constructed or the size of the field area tested is therefore dependant on the number of variables being tested, the area of land available for testing and on the number of surfaces being tested.

4.3. Rainfall simulation method

Rainfall application is vital to determine the hydraulic and water quality aspects of permeable paving systems. This can either be done using natural rainfall for field studies or using simulated rainfall within laboratory studies. Studies by Brattebo and Booth (2003) and Hunt and Steven (2004) both used natural rainfall events. This suited both studies as they were both large field studies needing wide scale rainfall application. In the case of Hunt and Steven they were concerned with the hydraulic behaviour of the system and therefore natural storm events of different durations and intensities were appropriate.

Anderson et al (1999) represented rainfall intensities and durations using a PVC box unit which stored water, beneath which was another sheet of PVC with holes drilled into to give drop size distribution and spatial uniformity. 15mm of rain was applied over durations of half an hour, 1 hour and then 2 hours; this represented the rainfall intensities/durations with a recurrence of approximately 5, 2 and 1 years in the Midlands, UK. This method was also used by Newman et al (2002), here 2 events a week were simulated at an intensity of 1.6mm/hr. Pratt et al (1999) conducted their study using a compressor driven rain maker simulating events with the same intensity as that used by Newman et al (2002). During the study by Rowe et al (2008) a simple bucket design with holes in base of a 19 litre bucket was used. 17 litres of collected stormwater was “rained” over each structure twice daily for 12 weeks. This was the equivalent to a 3cm rain event per bucket, at the end of the twelve weeks this was the equivalent to 3 times the annual precipitation of New Jersey. It can be seen that there are various rainfall simulator methods that can be used from highly advanced complicated methods such as that by Pratt et al (1999), or a simple bucket design like Rowe et al (2008).

5. Pollutants

Approximately half of the papers reviewed were concerned with the pollutant removal efficiency and capacity of the permeable pavement. The various types of pollutants applied and the pavements retention capabilities were reviewed.

5.1. Pollutants in Previous studies

In these studies a number of pollutants were applied to the test rig; including metals, oils, grease, nutrients were applied to the paving surfaces. Table 4 produced by Dierkes et al (2002) shows the average mean event concentrations of pollutants and nutrients from over 60 investigations in Europe for rain, roof and road runoff.

substance	unit	rain		roof runoff		road runoff	
		min	max	min	max	min	max
physico-chemical parameters							
el. cond.	[uS/cm]	28	223	25	269	108	2436
pH	[-]	3,9	7,5	4,7	6,8	6,4	7,9
sum parameters							
TSS	[mg/l]	0,2	52	13	120	66	937
BOD_5	[mg/l]	1,0	2,0	4,0	16,1	2,0	36,0
COD	[mg/l]	5	55	5	96	63	146
nutrients							
P_{tot}	[mg/l]	0,01	0,19	0,06	0,50	0,23	0,34
NH_4	[mg/l]	0,1	2,0	0,1	6,2	0,5	2,3
NO_3	[mg/l]	0,1	7,4	0,1	4,7	0,1	16,0
heavy metals							
Cd	[µg/l]	0,1	3,9	0,2	1,0	0,3	13,0
Zn	[µg/l]	5	235	24	4.880	120	2.000
Cu	[µg/l]	1	355	6	3.416	97	104
Pb	[µg/l]	2	76	2	493	11	525
Ni	[µg/l]	1	14	2	7	4	70
Cr	[µg/l]	2	8	2	6	6	50
ions							
Na	[mg/l]	0,22	20,00	-	-	5,0	474,0
Mg	[mg/l]	0,03	0,33	-	-	1,0	1,4
Ca	[mg/l]	1,10	67,13	1,00	19,00	13,7	57,0
K	[mg/l]	0,46	0,65	-	-	1,7	3,8
SO_4	[mg/l]	0,56	14,40	-	-	5,1	139,0
Cl	[mg/l]	0,20	5,20	-	-	3,9	669,0
organic substances							
PAH	[ug/l]	0,04	0,76	0,35	0,60	0,24	17,10
HC	[mg/l]	0,29	0,41	0,108	3,14	0,51	6,50

Table 4: Representative values of pollutants applied to test rigs from three sources (Dierkes et al, 2002)

Pollutant application depended on the study, some used natural rainfall such as Brattebo and Booth (2003), Gilbert and Clausen (2006) and James and Thompson (1997) with unknown concentrations of pollutants applied, whereas others such as Dierkes at el (2005) and Yong et al (2008) applied known concentrations of pollutants in an artificial rainfall mixture.

In the study by Dierkes et al (2005) an artificial traffic runoff mixture was made in a 1000 litre tank and sprinkled onto the rigs at varying intensities to simulate rainfall events. Concentrations of metals added to the artificial runoff were 3.6µg/l cadmium, 1600µg/l zinc, 240µg/l copper and 189 µg/l lead. The loads were increased ten fold to produce results for 18 years simulated rainfall. A similar method was used by Yong et al (2008) were artificial rainwater was “prepared by mixing sediment from a stormwater wetland with tap water of a known volume, topping up with specific concentrations of dissolved pollutants to achieve pollutant concentrations typical of urban land use” (Yong et al, 2008). Concentrations were as follows: TSS 150mg/l, total nitrogen 2.6mg/l, total phosphorus, 0.35mg/l, copper0.05mg/l, lead 0.14mg/l, zinc 0.25mg/l and cadmium 0.0045mg/l. They were distributed evenly across the rig during rainfall events to simulate 20years of real life operation.

5.2. Pollutant retention

The concluding results from approximately 30 papers found that pollution retention increased using permeable pavement systems although the level of retention for each pollutant varied depending on the following factors:

- Pavement surface and system
- Clogging
- Geotextile presence
- Pollution profiling

5.2.1. Pavement surface and system

The study by Brattebo and Booth (2003) compared the runoff concentrations from asphalt stalls to infiltration concentrations from permeable paving stalls and found that higher levels of the pollutants were retained within the permeable paving structures. Nine different storm events were sampled for water quality, testing motor oil, diesel fuel, copper, zinc and lead concentrations. The asphalt runoff contained significantly higher concentrations than the infiltrate for most measured pollutants, particularly of motor oil, copper and zinc. Levels of copper and zinc in runoff exceeded the water quality standards limits in all samples for copper and in all but one for zinc. However, for the infiltrate samples copper was undetectable in 72% samples for copper and 22% for zinc. This study therefore demonstrates the difference in water quality from runoff and from infiltrate through paving units, with paving units retaining much higher concentrations.

Gilbert and Clausen (2006) compared the runoff quality from asphalt, crushed stone and paver driveways in Conneticut. Metal concentrations were similar to those found in other studies, with copper levels in the asphalt and crushed stone being much higher than the freshwater aquatic toxicity threshold and lead and zinc being much lower. The paver produced the lowest concentrations of pollutants.

Dierkes et al (2005) evaluated the pollution retention capacity of the paving area of lead, zinc, cadmium and copper. All 5 laboratory rigs, each containing different joint fillers, showed high retention abilities of all the metals. It was found that the overall efficiency for cadmium and lead was over 99% and for copper 98% with zinc slightly higher than 94%. Highest pollution retention capabilities were found in the recycled blend material and the recycled concrete with the classic joint filler shows the lowest pollution retention capabilities (Dierkes et al, 2005).

The study by Bean et al (2004), conducted in the field on parking lots compared storm events runoff and infiltration water quality properties from an asphalt construction and from permeable interlocking concrete paving (PICP) from natural rainfall onto a site constructed two years before testing. Samples were analysed for total phosphorus, total suspended solids, nitrate-nitrite, total nitrogen, copper and zinc. Phosphorus had a much lower concentration in infiltrate from the PICP than in asphalt runoff and for copper, 3 of the 6 storms had a lower concentration of copper than in the runoff but the other 3 had similar values. No trends for total suspended solids and total nitrogen were determined from the study. Zinc concentrations were also much higher in runoff than in infiltrate, in some cases it was more than 9 times the concentration in the infiltrate. Throughout the six events measured the pollutants showed a downward trend in lower concentration for infiltrate than runoff.

Yong et al (2008), conducted a similar study (Table 5)within a laboratory on the treatment efficiency of three different pavers; porous asphalt, hydrapave and permapave. TSS concentration varied over the 3 different pavers, with porous asphalt 79%, Hydrapave 94% and Permapave 85% being retained within the structures. Similar results occurred across the 3 different pavers used for Total Nitrogen and Phosphorus removal.

Duration	TSS				TP				TN			
	Ave. Inflow (mg/L)	Removal %			Ave. Inflow (mg/L)	Removal %			Ave. Inflow (mg/L)	Removal %		
		PA	HP	PP		PA	HP	PP		PA	HP	PP
1 year	217	99	99	99	0.59	80	86	82	3.37	51	54	52
5 years	271	99	100	100	0.65	69	75	71	3.62	37	30	28
5.5 years (Storm 1)	111	65	86	76	0.49	28	38	29	2.87	14	18	17
10 years	127	99	100	98	0.47	66	75	68	2.75	34	24	25
15 years	138	99	99	99	0.57	61	73	67	3.10	40	27	27
17.5 years (Storm 3)	159	79	94	85	0.59	28	43	33	3.10	16	29	23

Table 5: Pollutant removal percentage (Yong et al, 2008)

5.2.2. Clogging

Table 6 shows the depths of ponding within the structures, indicating the levels of clogging during the study for the different structures. The structure with Hydrapave experienced clogging on the geotextile surface, limiting infiltration. Permapave was the only structure able to contend with the 100yr storm simulation for Melbourne.

Duration	Ponding depth indicating clogging (mm)		
	PA (above pavement)	HP (above geotextile)	PP (above pavement)
1 week – average rainfall	0	0	0
5 weeks – average rainfall	0	0	0
5.5 weeks – Flood Storm 1	***0***	***0***	***0***
10 weeks – average rainfall	0	0	0
10.4 weeks– Flood Storm 2	***0***	***60***	***0***
15 weeks – average rainfall	0	0	0
17.5 weeks – Flood Storm 3	***2***	***110***	***0***

Nb: 1 week of inflow corresponds to 1 and 0.5 years of operation in Melbourne and Brisbane.

Table 6: Ponding depth for the various permeable pavers (Yong et al, 2008)

5.2.3. Geotextile presence

The presence of an upper geotextile was found to be particularly important during studies concerned with oil retention and biodegradation; however there have been no known studies comparing the benefits of the inclusion of an upper geotextile against not including one.

Pratt et al (1999) conducted both a laboratory and field study to simulate crank case leakage. The apparatus contained both an upper and lower geotextile. An oil dripper was used to drip oil onto the surface over a period of ten hours to simulate crank case leakage. Oil application started on day 19, on day 48 250ml of oil degrading microbe mixture and 100ml of proprietary liquid fertiliser were applied. A further 100ml of liquid fertiliser was applied on day 88 and 183, day 237 saw 18g of osmocote slow release fertiliser applied (Pratt et al, 1999). It was observed from the experiment that only 2.4% of the oil applied was not retained within the system and that a structure's efficiency at degrading oil is dependent on nutrient supply.

Two reports by Newman looked at the retention and clogging properties of porous paving systems. The first report included an upper geotextile and looked into the effects this had on the clogging and bioremediation of oil within the system. Newman et al (2001) found that 99.6 % of oil was retained in porous paving systems, compared to 49.6 % within a comparison box built using asphalt.

The second study by Newman et al (2002) studied the bio-degradation by microbial communities in 3 different sized structures, each with different concentrations of oil applied per week. All rigs, small, medium and large were constructed with an upper geotextile Some of the rigs were inoculated with Biothreat HD, an oil degrading microbial inoculum and some of the rigs also had a slow release fertiliser added, small rigs 0.22g, medium rigs 1.6g and large rig 18g. As with previous studies, oil was applied using a dripper to simulate vehicle engine leakage. Both the large and the medium rigs inoculated or not, retained 99% of the oil applied. For medium rigs the amount of oil on the geotextile was slightly less for non inoculated rigs compared to inoculated rigs (8.9% to 9.9%).

Puehmeier and Newman (2008) looked at the oil retaining properties of paving rigs each containing a different sub base arrangement. One had no geotextile present, while the other three had varying arrangements, including one with the new geotextile being tested located between the subbase and bedding layer, another with the Inbitex (Formpave UK) geotextile, again located between the subbase and bedding layer and the final rig contained two geotextiles, one between the subbase and bedding layer and another below the geotextile.

Rainfall was applied over a period of 3 hours to the rigs and $600ml/m^2$ of oil was applied. Rainfall events were repeated 18 times using the same concentrations, with the exception of the rigs without a geotextile as after the first event it was evident that the concentrations in the effluent were exceeding the upper range of the analytical method. It was concluded that the new geotextile system offered an improvement in the efficiency of the geotextile compared to the standard one used, but both systems still had better oil retaining qualities than that of the unit without a geotextile.

In a review by the Environmental Protection Group, in 2007 on studies by Coventry University it was stated that on breaking down the pavements they found most of the oil trapped in the pavement was on the upper geotextile. This is a belief reflected by manufacturers, Charcon (n.d.) and Hanson Heidelberg (n.d.), who state that the upper geotextile is incorporated for the retention and biodegrading of all oil spillages. Hanson Heidelberg (n.d.) statements show that they also agree with this theory and believe it has the added benefit of providing additional filtration prior to discharge into the underlying layer.

5.2.4. Pollution Profiling

Studies by Dierkes et al (1999) and Legret et al (1996) discuss pollution profiling within the structure of the permeable paving unit. In the study by Dierkes et al (1999) all materials within the rig and test bed were sampled at different depths to obtain information about pollution profiling once the testing regime had been completed. It was found most metals were precipitated in the upper 2cm of the porous concrete structures especially copper and lead, with zinc and cadmium in higher concentrations up to 8cm. Within the subbase higher concentrations of metals were found up to depths of 20cm for cadmium and lead and 10cm for lead and copper after the equivalent of 50 years rainfall loaded with pollutants had been applied.

Similarly the study by Legret et al (1996) took samples at different levels of the soil and structure after a trench within the street was opened. Legret et al (1996) determined that heavy metals mostly accumulate on the surface of the geotextile. Underneath the structure, metals were found not to migrate beyond 15cm and after 4 years the soils appears to be uncontaminated by heavy metals

For the purpose of our study assessing pollution profiling will be done by collecting samples at varying depths within the structure after the test regime has been completed.

6. Hydraulic studies

Hydraulic studies are required to determine infiltration capacity, runoff volumes and surface runoff rates. These factors are affected by precipitation intensity and infiltration rate and are important when considering how to control storm water at source or on-site. Similarly to the pollution retention investigation, it is shown that infiltration capacities are increased significantly with permeable pavements in comparison to impermeable paving systems, however once again the degree of infiltration is dependent on a number of factors:

- Paving surface.
- Joint filler, bedding and spacing.
- Clogging.
- Geotextile influence.

6.1. Paving surface

A laboratory study by Yong et al (2008) revealed that the type of paving surface impacted on the infiltration rates. They compared two systems: Permapave (PP) and Hydrapave (HP), PP was found to be the most porous while HP had the highest infiltration capacity.

In a laboratory experiment by Gilbert and Clausen, (2006) they found that when comparing asphalt, paver and crushed stone driveways; the infiltration rates were 0, 11.2 and 9.0 cm/h respectively. The reduction in runoff from asphalt to paver surface was 72% and to crushed stone was 98%. However, infiltration rates at both the paver and crushed stone driveways declined somewhat over the course of the study, this depended on the thickness of the base course, although infiltration rates were still greater than the zero infiltration measured on the asphalt driveways.

6.2. Joint filler, bedding and spacing

Gilbert and Clausen, (2006) observed that the lag time between infiltration and discharge in the paver and gravel sites is dependent on the pore spaces in the sub-base and therefore the type of sub-base. However once the sub-base is filled it is controlled by the intensity of precipitation and rate of infiltration. Anderson et al (1999) designed eleven test rigs on a laboratory scale and found that, the lag time varied for each structure and rainfall event in response to the varying particle sizes of bedding gravels and also as a product of rainfall intensities applied. However, when examining a single intensity of 15mm for one hour, an increase in attenuation was observed within the dry permeable pavement structure which has small grain substrate; 55% of a 15mm/hr storm of 1hr duration was retained.

However, the importance of the sub-base and sub-soil in determining pore spaces for water infiltration and exfiltration performance is also reflected in a field study carried out by Bean et al (2004). They carried out water quantity measurements on two Permeable Interlocking Concrete Paver (PICPs) parking sites in North Carolina, Cary and Swansboro, over 2 and 10 months respectively. They found that the site at Cary, which was located in clay soil, had a surface infiltration of 230 cm/h and that runoff was attenuated in three ways (1) Runoff Volume (66% of water entering the site left through exfiltration, leaving 34% to runoff), (2) Peak Runoff Rate (reduced by 67%) and, (3) Peak Outflow Delay (78 minutes). The Swansboro site, located in sandy soil, was able to attenuate all of the 107cm of rainfall that occurred from March 1st to December 31st in 2004, allowing no water to runoff. These results were a result of the high porosity of the sandy soil compared to the low porosity of the clay at the Cary site.

6.3. Clogging

Without maintenance of the permeable paving structures the infiltration rates decline significantly (Scholz and Grabowiecki, 2007 and Swisher, 2002). Bean et al, (2004) demonstrated that infiltration rates can reduce by up to 45% without maintenance; the median average infiltration rate was 5.0 cm/hr prior to maintenance but increased to 8.0 cm/hr once maintenance was carried out. As another illustration of the potential problems with clogging they observed that PICP sites free of fines have significantly higher infiltration rates than PICP sites with sandy fines present in this study. Berbee et al, (1999) found that clogging was a significant problem in pervious asphalt in comparison to other surfaces.

6.4. Geotextile influence

In a study by Bouteligier et al (2007) an upper geotextile was used to prevent silting of the base layer. However, due to clogging of the geotextile, the permeable structure lost some of its hydraulic capacities. Rowe et al (2008) found that systems with geotextile liners infiltrated slower than those without. Peak exfiltration rates were 7.2% lower for lined bins compared to unlined bins. In Yong et al (2008) comparison of the hydraulic action of Permapave (PP) and Hydrapave (HP) showed that although the sub-bases of both systems had a similar infiltration capacity, the HP sub-base contained a geotextile layer, which acted as a partial barrier. The barrier action of the geotextile on infiltration rates is dependent on the type of geotextile used. Gomez-Ullate et al (2008) carried out a laboratory experiment to compare a normal non-woven polypropylene/polyethylene geotextile with a one way geotextile (Inbitex-geomembrane geocompose). As expected, the one way geotextile retained water and made the percolation of water slower than in other treatments because of its impervious nature. The reduction in infiltration can be partially explained by the ‘ponding action’ that occurred after repeated experiments on test rigs created by Yong et al (2008).

7. Outcome for Marshalls

Marshall's Priora Paving system is constructed to a specific design methodology and sub base specification in line with BS 7533-13:2009, BS EN13242: 2002 and other British Standards soon to be superseded by European standards.

In general terms, the construction consists of Priora Paving blocks laid on a laying course aggregate. A geotextile layer may be placed between the laying course and the sub base aggregate depending on site specific conditions and a further impermeable geotextile membrane may be utilised to prevent water migrating to the underlying watercourses or sensitive soils.

For the purpose of this trial the following specification of materials will be used:

- One layer of 200 x 100 x 80mm Priora Paving blocks
- 50mm depth of 2/ 6.3mm laying course graded aggregate
- 200-350mm depth of 4/20mm Open Graded Crushed Rock (OGCR) or Open Graded Crushed Gravel (OGCG) sub-base aggregate.
- Impermeable membrane liner

For the purpose of this study it has been decided to construct similar laboratory test rigs to that used by Rowe et al (2008) as shown in Figure 1 although at present the rigs will be 1m x 1m to aide with ease of calculations and to provide a large enough test site. Unlike the study by Rowe et al (2008) the test rigs for this project will contain a perspex front such as that in the study by Yong et al (2008) to enable any ponding on the surface of the geotextile to be seen. Ten boxes will be constructed; five with a geotextile and five without, the study by Rowe et al (2008) is also the only known study to carry out simultaneous studies on structures with and without an upper geotextile. There will be two control structures and eight which will be used for applying pollutants too.

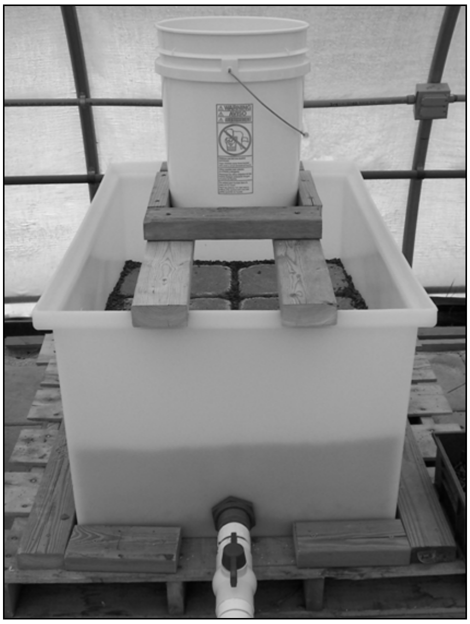

Figure 1. Laboratory Design by Rowe et al (2008)

As mentioned in section 1.1.3 there is a variety of methods of applying rainfall to the test rig. Some are very complicate such as those by Anderson et al (1999) but other such as the study by Rowe et al (2008) is a simple and effective method. This study will use a simply rain simulator design consisting of a pipe array system to apply the average rainfall intensity of Scotland to simulate a number of events and years of study. An exact event schedule is still to be determined.

Having examined the wide range of pollutants applied to various test sites and rigs there are a number which crop up again and again; these pollutants are metals and nutrients commonly found in round runoff. For this study a number of metals, oils, nutrients and salts will be applied to the test rigs surfaces and the concentration within the infiltrate will be analysed to determine the performance of the structure.

8. Conclusions of Review

There are no definitive studies to prove that the removal of the upper geotextile from a permeable pavement structure will impede/enhance pollutant removal or impede/enhance the hydraulic performance as there have been no comparative tests carried out on the performance of the same permeable paving system with and without the upper geotextile layer. Rowe et al (2008) is the only known study at the time of this literature review to have done this but the results from the second stage of the study, examining the role of microbial colonies in pollutant removal performance, are yet to be published. Other studies however do appear to suggest that the geotextile layer is likely to impact on oil retention, clogging and therefore water infiltration rates. By carrying out a comparative study it is hoped that the benefits or otherwise of using an upper geotextile can be identified.

Appendix D

Geotextile Review

Review of Geotextiles currently available for permeable paving systems

Authors

J. Mullaney Ma

L. Samson BSc

C. Jefferies BSc, MSc, PhD

urbanwater TECHNOLOGY CENTRE

Contents

1 Objective

This review compares the mechanical, physical and hydraulic properties of geotextiles that would be considered suitable for the application of an upper geotextile within a permeable paving system. The geotextiles will be compared to the geotextile currently used by Marshalls Plc, Terram 1000 which is manufactured by Terram.

2 Types of geotextile

Geotextiles can be characterised as being 'woven' or 'non-woven'. Woven geotextiles (Figure 1) are formed by interlacing two or more sets of yarns, fibers, or filaments where they pass each other at right angles. (Holtz, 2009) Specific weaving methods create four types of geotextiles: monofilament, slit film, multifilament and fibrillated. Monofilament geotextiles offer little resistance to through flow and are generally made from polyethylene (HDPE) or polypropylene (PP). A multifilament yarn consists of many fine continuous filaments that are held together by twisting the strands and fibrillated tapes are made by splitting and twisting extruded films. Woven slit film are produced with yarns formed by longitudinally splitting a polymeric film to form a slit tape yarn, however this type of woven geotextile is not suitable in drainage and filtration applications and therefore not suitable in permeable pavement structures. (John, 1987)

Woven geotextiles are characterized by their excellent strength properties and are generally less expensive than non-wovens of the same strength. (Holtz, 2009)

Figure 1. Example of a split tape woven geotextile manufactured by ABG.

Non-woven geotextiles (Figure 2) are typically manufactured by putting small fibers together in the form of a sheet or web, and then binding them by mechanical, chemical and/or solvent means. They are grouped into 3 categories: needle punched, chemical bonded or heat bonded. (Holtz, 2009) Non woven geotextiles are generally not as strong as their equivalent woven geotextile but they exhibit better filtration and separation properties. (Cook, 2003) For this reason non wovens are the preferred geotextile in permeable paving applications; over 70 % of the reviewed geotextile manufacturers would supply a non woven geotextile for this application, this includes Terram 1000.

Figure 2. Example of a non woven geotextile (Terram 1000)

3 Geotextile construction materials

The polymers used to construct both woven and non-woven geotextiles in this review are synthetic polymers, either polyester or polypropylene, however two companies, Terram and WTB Geotechnics construct their geotextiles using a mixture of both polymers.

Polyester and polyolefins such as polypropylene are hydrophobic materials (water repellent materials). Whilst this is advantageous in circumstances that require water to be trapped above the surface of the geotextile it may lead to pooling within a permeable pavement structure if geotextiles with the incorrect flow rate and permittivity are used. Polyesters and polypropylene materials are highly resistant to chemical and biological degradation. (Holtz, 2009)

The majority of manufacturers use polypropylene in the construction of their geotextile. This preference could be attributed to their physical/mechanical properties as a study of the ‘Chemical aging effects on the physio-mechanical properties of polyester and polypropylene geotextiles’ by Mathur, Netravali and O'Rourke in 1994 revealed that polyester deteriorates over time under both acidic and alkaline conditions with the degradation being more severe under alkaline conditions. However, the polypropylene geotextile, was relatively unaffected by changes to the pH conditions and showed no changes in strength. However there was an observed increase in crystallinity in the initial period of aging for both polyester and polypropylene.

4 Geotextile applications

In general the geotextiles can be used for a number of applications, for example Bonar Technical Fabrics state that their ‘NW9: Non Woven Geotextile’ is suitable for use as a separation and strengthening layer under new roadways, car parks, industrial units and as a fliter surround in the construction of a french drain or granular drainage blanket. Only 2 of the reviewed companies stated they could provide specific geotextiles designed for use within permeable pavements; the companies are Terram who manufacture Hanson Formpave’s Inbitex and Permavoid, the manufacturer of Althon Limited’s SEL Sudstex Permafilter, Charcon’s Permafilter (Figure 3) and Blockleys Smart Geotextile.

Figure 3. Charcon’s Permafilter manufactured by Permavoid.

Hanson Formpave’s ‘Inbitex Thermally Bonded Nonwoven Geotextile’ is used in their Aquaflow permeable paving system. Formpave state that “during the manufacturing process, small dishes are created on the surface of the hairs from which the geotextile is manufactured. This is very important in the early establishment of a microbial biomass which is responsible for eating and degrading oils in the water. It is also important during dry periods when the microbial population can retreat into the dishes where moisture is to be found. Thus when it rains again the microbial biomass is quickly re-established. With de-icing salts a large proportion of the microbes will be killed, but those which survive develop immunity to salt and a salt-resistant community develops." These microbes have the capacity to consume 400g of hydrocarbon per annum and any non-degradable matter such as heavy metals and silts are trapped in the laying course, so optimising the cleansing of water entering the Aquaflow paving system. (Hanson Formpave, 2010)

The three geotextiles manufactured by Permavoid are manufactured principally to enhance hydrocarbon removal by trapping the hydrocarbon on the surface cavities formed by needle punching the fabric, then allowing microbial biodegradation to occur. Test results by Althon and Charcon claim that the geotextile can degrade catastrophic spillages up to a maximum of 6 litres of oils per 10m2 of geotextile with an effluent discharge at maximum oil retention of less than 10 parts per million. (Althon, 2010 and Charcon, 2010)

5 Geotextile Properties and Functions

The functions of geotextiles are divided into five categories: Separation, Filtration, Drainage, Protection and Reinforcement. Each of the reviewed geotextiles performed at least two of these functions but usually more.

In order to perform these functions, in a transportation environment, the geotextiles have to conform to set standards. Guidance on the properties of geotextiles for use in permeable pavements is given in BS EN 13252:2001 ‘Geotextiles and geotextile related products’- characteristics required for use in drainage systems and also used BS EN 13249:2001 ‘Geotextiles and geotextile related products’ – characteristics required for use in the construction of roads and other trafficked areas (excluding railways and asphalt inclusion). (Interpave, 2006). In the US, the American Association of State Highway and Transportation Officials (AASHTO) developed the AASHTO M288-06 standards: “Standard Specifications for Geotextiles,” which addresses the following applications: Subsurface Drainage, Stabilization, Separation, Permanent Erosion Control, Sediment Control, and Paving Fabrics. (Centexbel, 2009 and ASTM, 2010)

The geotextiles are tested in 3 different areas: Mechanical, Hydraulic and Physical properties. Table 1 shows the general tests carried out for each property and its associated European and American standard.

Property	**European Test Method**	**American Test Method**
Mechanical		
Nominal Tensile Strength, Tult kN/m (lb/ft)	EN ISO 10319	ASTM-D4632
Elongation at Nominal Strength, %	EN ISO 10319	ASTM-D4632
Trapezoid Tearing Strength N (lb)	---------------	ASTM-D4533
Static Puncture Resistance (CBR) N (lb)	EN ISO 12236	ASTM-D6241
Cone drop perforation (mm)	EN ISO 13433	--------------
Physical		
Mass ±20% g/m2 (oz/yd2)	EN ISO 9864	ASTM-D5261
Thickness mm	EN ISO 9863	ASTM D5199
Hydraulic		
Flow Rate L/min/m^2 (gal/min/ft^2)	EN ISO 11058	ASTM-D4491
Apparent Opening Size(O95) mm (U.S. Sieve)	EN ISO 12956	ASTM-D4751

Table 1. European and American Test Standards for Geotextiles. (Centexbel, 2009 and ASTM, 2010)

The Tensile Strength test is designed to simulate the loads and stresses applied to fabrics after installation in the ground. The values quoted are in KN/m which is the force (load) needed to pull apart 1m width of the fabric. (Shukla, 2002)
The tensile strengths of the reviewed geotextiles varied generally between 8 to 12 KN/m with only the Don & Low product HF550 exhibiting a higher tensile strength of 27 KN/m. Therefore, the review shows that there is little variation between the Marshalls geotextile and those supplied by other manufacturers.

The elongation at peak strength test is designed to show how much the product is stretched at its peak strength i.e. when the fabric has been stretched to the point just before it starts to be pulled apart. (Shukla, 2002) There is a wide variation throughout the geotextiles with values ranging from 28 to 90 % elongation. The Marshalls

Terram 1000 is 28% which is the same value as the Don & Low product HF550 and the Inbitex material also manufactured by Terram and offered as a specific permeable paving geotextile.

The Static Puncture Test simulates stones being slowly pushed against the fabric as they may be expected to occur in a separation / filtration application.
The test method is designed to show a fabric's resistance to a 50mm diameter plunger being forced through the fabric at a set speed of 50 mm per minute. (Shukla, 2002)
For example, for Terram 1000, 1500 Newton's is the maximum force that the fabric can, on average, withstand- as the force is increased past this point the plunger will eventually push through the product. Other geotextiles predominantly displayed values between 1400 and 1600 N with only four geotextiles outwith this range: Don & Low HF550, Source Control Systems Ltd SCS GT1900, Tencate TS30 and the Wallbarn 200PPX. The static puncture test results do not have an influence on any other properties.

The Cone Drop Peforation test specifies a method to determine the resistance of geosynthetics to penetration by a steel cone dropped from a fixed height. The degree of penetration is an indication of the behaviour of the geosynthetic when sharp stones are dropped on its surface. (Shukla, 2002) This test is not displayed by all manufacturers data specifications but values vary between 14 and 35mm. The cone drop penetration test results do not have an influence on any other properties.

The Pore Size or Characteristic Opening Size test is designed to test the average size of the holes in the fabric. A known weight and range of very fine glass beads (used to simulate soil particles) is placed on the fabric with water gently being sprayed onto the beads and the fabric. The fabric is then vibrated and the weight of the beads that goes through the fabric onto a filter paper is recorded. The information is used to calculate the average size of the holes in the fabric. (Shukla, 2002) For example for Terram 1000 the average size of the opening is 150 microns.

The results of other geotextiles vary widely from 70 to 380 microns however this does not affect the permeability or any other property.

Permeability: This test takes the average of 5 specimens to measure how fast a 50mm column of water moves through the product. The data is then expressed in terms of how many litres of water would go through a square metre of fabric in one second assuming a 50mm head of water. (Shukla, 2002) For example, for Terram 1000 if one had a sheet 1m2 and the depth of the water could be maintained at 50mm, 100 litres would move through the fabric in 1 second. The results of the other geotextiles varied between 36 and 120 $l/m^2/s$ and is generally a function of the weight and thickness of the geotextile. The heavier the geotextile the less the permeability. The Charcon and Althon Permafilters have the least permeability out of all the geotextiles and are also the heaviest. They are also the only geotextiles to claim to have enhanced hydrocarbon removal in comparison to other geotextiles currently on the market.

6 Conclusions of Review

With the exception of the geotextiles manufactured by Permavoid; the Althon Limited's SEL Sudstex Permafilter and Charcon's Permafilter , the geotextile currently used by Marshalls Plc, Terram 1000 has similar properties to others on the market and any changes to the usage of this product may down to cost savings alone. Further investigation of the testing methods may be required to validate this conclusion.

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