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Hydrocarbon Retention and Biodegradation in Conventional and Improved Pervious Pavement Systems

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PhD by Portfolio

By

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Coventry University

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Part 1 – Critical Overview

Selective Glossary and Abbreviations

The purpose of this glossary is to provide definitions of terms which are considered not to be in common usage and to provide definitions of the abbreviations used. It also provides the reader with a brief explanation as to the reason for adopting certain of the abbreviations where there is a potential for confusion.

CeePy® block- Pervious pavement block designed by Professor Chris Pratt in which the shape of the block generates, when laid together, a pavement surface,

CNC- Computer Numerical Control: This term is applied to automated machining and related processes in which the control of the device is carried out by a computer rather than a human operator. The process can facilitate the repeated production of complex two and three dimensional artefacts. In this work the use of CNC was restricted to a laser cutting process for the production of prototypes of floating absorptive mats for use within the FMD (defined below).

DGGE- Denaturing Gradient Gel Electrophoresis: A form of electrophoresis which uses a chemical gradient to denature sequences of DNA as they move across an acrylamide gel under the influence of electrophoretic flow. The denaturation unwinds the double helix and prevents further electrophoretic migration. In this work DGGE was applied to fragments of DNA coding for parts of the 16S ribosomal RNA found in the ribosomes of bacteria (and in the mitochondria of eukaryotes). The fragments of DNA are produced using **PCR** (defined below) and **primers** (defined below) which are designed to create a sequence terminating at one end with a section of a sequence where it is very difficult to induce separation. This means that conditions in the electrophoresis gel are never sufficient to produce single stranded DNA.

EPSRC- Engineering and Physical Sciences Research Council

EWRI- The Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE): an organizational entity within the ASCE whose constitution requires it to: “strive to be the leader for integrating technical expertise and public policy into the planning, design, construction, operation, management, and regulation of environmentally sound and sustainable infrastructure involving air, land, and water resources” (extracted from EWRI website).

FMD- Floating Mat Device

HRI- Horticulture Research International (latterly Warwick HRI): A now defunct government funded organisation tasked with carrying out horticultural research and development and transferring the results to industry in England. Warwick HRI was formed on 1 April 2004 following the integration of Horticulture Research International’s sites at Wellesbourne and Kirton with the University of Warwick. In November 2009 Warwick University announced that it "has decided to close Horticultural Research International, which it took over in 2004, as the centre was losing the University £2 million a year". (The detail within this definition is largely derived from the Horticultural Research International entry in Wikipedia)

IPR- Intellectual Property Rights

ITS primers - Primers (defined below) which are suitable for the replication of DNA which codes for ITS (internal transcribed spacer) RNA, a section of non-functional RNA situated between structural ribosomal RNAs. This DNA is poorly conservative and several different sequences can occur within a population of microorganisms.

KTP- Knowledge Transfer Partnership: A UK Government research funding scheme (a successor to the Teaching Company Scheme (TCS)) in which industrially related research is enabled through funding the appointment of a KTP Associate (of graduate or post-graduate status) and involving the collaboration of industrial or commercial partners with “knowledge based partners” (usually universities).

LTC- Landfill Tax Credit Scheme: Now called The Landfill Communities Fund. The scheme enables landfill site operators to claim tax credit for contributions they make to approved environmental bodies for spending on projects that benefit the environment. The environmental bodies are those enrolled by Entrust, the regulatory body for the scheme. Until April 2003 landfill operators were able to direct funds to support research and development activity and part of the work in this portfolio was funded by this scheme through a grant made by one of these bodies.

MPPS- Macro-Pervious Pavement System: A member of a sub-class of pervious pavement systems where the vast majority of the surface is impermeable and water is directed underground by numerous relatively large and discrete openings rather than through a porous surface or via relatively small infiltration channels. It must be recognised that the distinction between a pervious pavement and a macro-pervious pavement is unclear as there is no accepted sub-division based on the size of the penetration. The MPPS may utilise specialist devices to allow water to enter through the paved surface whilst achieving a degree of oil and sediment retention but to fit the definition this is not mandatory.

OSCD- Oil Separating Channel Drain.

PCR- Polymerase Chain Reaction: The process by which in vitro replication of DNA for experimental purposes is carried out.

Permaceptor® - The registered trade name used to describe a very shallow gravity oil separator situated directly below a paved surface. The basic principal is that the gravity oil separation function is dispersed below the pavement rather than being concentrated in a small area as a centralised, deep tank. It was originally intended to be used with pervious surfaces only and to occupy a majority of the volume of the pervious pavement system as a continuous entity. It has also found other applications including its use in conjunction with, and immediately downstream of, traditional gulley pots.

PP- Pervious Pavement : A paved area which is capable of allowing the entry of water into the subbase zone for it to be either infiltrated into the groundwater system or temporarily stored until released in a controlled manner into a surface water body, a drain or a sewer. The aim of the device is to reduce the peak outflow to surface water systems or sewers such that the carrying capacities are not exceeded. Whilst originally designed solely for this purpose advantage is commonly taken of the pollution reduction capabilities of the device. In this document the abbreviation is used solely in its singular sense as a convenient construct to distinguish it from the abbreviation PPS which (in this document) is restricted to use in the plural. Using the convention adopted here "Pervious Pavements" would be abbreviated as PPs.

PPS- Pervious Pavement Systems: Strictly speaking, those drainage systems which make use of a pervious pavement as the primary means of achieving both stormwater flow control and pollution reduction/prevention. In other works it is commonly used to represent the term "Pervious Pavement System" in a singular sense but within the convention used in this document it is restricted to the plural (largely to avoid the need to use the abbreviation PPSs which is rarely used elsewhere). Where the singular is required the partially abbreviated term "PP system" is used. Whilst a pervious pavement on its own could constitute a pervious pavement system (if it were an infiltration system alone with no provision for a piped overflow) there are normally other components which make the term "system" more appropriate (including, for example, a perimeter curb to limit the direction in which overland flow might occur in "failure" situations).

Primer- A strand of nucleic acid that serves as a starting point for DNA synthesis. They are needed for replication of DNA (or RNA) because DNA polymerases, which catalyze this process, can only attach new nucleotides to an existing strand of DNA.

SUDS- Sustainable Urban Drainage Systems: The original name for the philosophy of stormwater drainage which aimed to imitate as far as possible the drainage characteristics of a catchment which was unaltered by human activity. Originally applied to highly urbanised catchments (and hence the upper case U) it later became applied to decreasingly urbanised catchments leading to some workers adopting the alternative (more generic) acronym with the lower case u. In this document the older acronym has been utilised almost exclusively to reflect the “hard” nature of the SUDS systems to which this work has been applied.

SuDS- Sustainable Drainage Systems: The more recently adopted acronym which acknowledges the value of an appropriate philosophical approach to all stormwater drainage including the drainage of rural areas. At the start of the programme of work described in this portfolio this alternative acronym was little used but it is now used increasingly both in recognition of its more generic nature and because it often better fits the application to “soft” and “green” SuDS as opposed to the “harder” SUDS that are used in intensively developed areas (including pervious pavement systems and large scale subsurface detention tanks). It should be recognised that the distinction between SuDS and SUDS is very blurred and only of little consequence. It should also be recognised that it is now common to use both “SUDS” and “SuDS” as adjectives as exemplified by their use in, for example, “SUDS system” or “SuDS approach”.

TPH- Total Petroleum Hydrocarbons: Although the term may appear to be straight forward, this is not the case, as the reported value is significantly dependent on the method used and on the materials used to calibrate the method.

WREN- Waste Recycling Environmental Limited: An environmental body created by Waste Recycling Group plc. which distributes Landfill Tax Credits under the 1997 Landfill Tax Act.

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CHAPTER 1
INTRODUCTION

This chapter seeks to place the outputs presented in the portfolio into their environmental and academic contexts. It presents a background to the problems that this area of research were intended to address and briefly identifies the philosophical framework, the concept of Sustainable Urban Drainage Systems (SUDS), within which the outputs presented sit.

1.1 Structure, Context, Aims and Objectives

The Outputs presented in this portfolio relate to research carried out on Pervious Pavements Systems (PPS). The Pervious Pavement (PP) was originally devised for flood prevention but it is also recognised as having significant water pollution prevention capabilities. The portfolio includes four journal articles and one from a conference proceedings as well as two patented inventions. The patents themselves inevitably provide little detail of the research effort which created them and thus the "Output" has been taken to include both the relevant patent(s) and, in each case, at least 1 refereed publication as examples of the development process. For one of these outputs there is a URL to a short video clip to help the reader understand the rather complex combination of inventions as a system rather than as just a collection of parts.

1.1.1 Aims and Objectives

The main aims of the programme of research for this portfolio were:

- To understand and demonstrate the capabilities of, and mechanisms taking place within, PPS and related systems in relation to their oil retaining and degradation properties. This was carried out with the view of improving the acceptability of the PP concept to developers, regulators and the wider community and to aid optimisation of these systems.

- To explore whether significant improvements in performance and utility can be achieved by modifying PPS such that use can be made of additional oil retaining and degrading mechanisms, not available in conventional formats, and, in particular, to do so with the possibility that catastrophic losses of oil from vehicles could occur.

From these two aims the following objectives were established:

a. Determine whether PPS are capable of maintaining complex, self sustaining, oil degrading, communities of microorganisms over extended periods and to identify the external inputs required to achieve this.
b. Develop a means by which required inorganic nutrients could be made available to the oil degrading microorganisms in a PP in a highly effective way whilst minimising losses of inorganic nutrients to ground or surface waters.
c. Study the response of traditional PPS to catastrophic vehicle oil losses and explore a practical system to allow the use of the PPS in highly sensitive environments or high oil spill-risk areas.
d. Establish a practical approach to the use of pervious subbases in the absence of a pervious surface where developer resistance is leaning towards positive drainage because of mistrust of the pervious surfaces available

1.1.2 Document Structure

The current chapter continues with a brief introduction to the problems addressed in this portfolio. Chapter 2 deals with Outputs 1-3 and largely addresses objectives a. and b. (being largely concerned with the biodegradation process). These Outputs are primarily associated with increasing understanding and establishing limitations of PPS. Chapter 3 covers Output 4 and largely address objective c. with the development and validation of novel PPS which intimately incorporates an oil gravity separator. Chapter 4 provides an overview to Output 5. It addresses objectives c. and d. through the development of devices that facilitate the, counter intuitive, “pervious pavement” without a pervious surface. Chapter 5, addresses objective b. and is based around Output 6. Although this objective is also addressed in earlier chapters Output 6 is very much more of an applied piece of work in that it outlines part of the process of developing improved geotextiles for PPS application. The document then proceeds, in Chapter 6, to discuss critically how this work might have been improved, to consider ongoing and future work and to make some concluding remarks in the context of the aims and objectives outlined above. Throughout this document detailed reference is made to other examples of the candidate's publications which have been critical precursors to portfolio Outputs or which represent a significant development from them.

1.2 The Modified Hydrological Cycle and Water Quality

Even in densely populated countries largely unmodified drainage routes still make up the majority of the outflowing part of the hydrological cycle. Such "minimally-modified" drainage systems, which provide both flow control and aquifer recharge, have been described as "a spatially distributed control system" (Sidek *et al.,* 2002).

Although positive drainage had been accepted as the only stormwater disposal solution for urban areas from the 19th century until late into the 20th century it is now recognised (e.g. DEFRA, 2008; White and Howe, 2002; Chen *et al*., 2010) that using this approach to deal with surface water runoff has serious disbenefits. When the impervious area within a catchment increases beyond a significant level, positive drainage can initiate sudden rises in water levels in receiving water courses during heavy rain (Chen *et al.,* 2010). This inevitably increases the risk of fluvial flooding downstream. It is also self-evident that overloading the local capacity of drains and sewers can also lead to pluvial flooding in urban areas (Chen *et al.,* 2010), often accompanied by discharges of raw sewage to the surface by overloaded combined sewers.

Furthermore, surface water runoff can be highly polluted with contaminants which have been accumulating on impermeable surfaces and are then re-released. Pollutants are wide ranging and appear at an extensive range of concentration levels (D'Arcy *et al.,* 2000; Ellis and Chatfield, 2006; Gnecco *et al.,* 2006; DEFRA, 2008). Whilst not a universally observed phenomenon (Sansalone *et al.,*1998), the first flush during a rain event is often identified as the most polluted fraction

(Campisano and Modica, 2003; Ferreira *et al*. ,2002; Li *et al.,* 2007; Soller *et al*., 2005).

1.3 Sustainable (Urban) Drainage Systems

In the late 20th century it was realised that rapid stormwater removal combined with the increased burden of runoff due to urbanization was resulting in increased risk of flooding (Andoh, 1994; Schmitt *et al.,* 2004; Neal *et al*., 2009; Chen *et al.,* 2010; Smisson, 1979). This realisation initially led to the implementation of both on-site and off-site detention, aiming to limit flow-rates to those that occurred prior to the development of the land. Some of the designs used were highly inventive, even aesthetic, and some of these developments have accrued something of an "academic tourism" identity with certain famous features being regularly visited by study groups e.g. Hopwood Park motorway service area (Heal *et al.,* 2009) and various parts of the Dunfermline Eastern Expansion (Jefferies, 2001).

This enlightened appreciation of the issues resulted in an approach called "Sustainable Urban Drainage Systems" (SUDS) in Europe (Wild *et al.,* 2003; Woods-Ballard *et al.,* 2007) (also commonly called "Sustainable Drainage Systems" (SuDS)). Terms such as "Best Management Practices" and "Low Impact Development" find favour in the USA (Ice, 2004; Dietz and Clausen, 2008). Rather than simply consisting of an assemblage of techniques, SUDS provide a philosophy which aims at a holistic approach to management of rainwater runoff. The source control doctrine, detaining and treating water close to the point of deposition (Pratt, 2004; Pratt *et al*., 2002; CIRIA , 2001), is an important component of the SUDS philosophy. As well as providing discharge control, SUDS should also provide for the treatment of polluted surface waters utilising the natural processes of sedimentation, filtration, adsorption and biological degradation and PPS offer an excellent example of this approach.

1.4 Pervious Pavement Systems (PPS)

1.4.1*Traditional PPS*

PPS have received substantial attention from researchers, particularly with respect to their use for vehicle parking areas (e.g. Pratt,1995a; 1995b; Pratt *et al*.,1996;1999; Booth and Leavitt, 1999; Brattebo and Booth, 2003; Bayon *et al.,* 2005; Dierkes *et al.,*1999; MacDonald and Jeffries, 2001; Rodriguez *et al.,* 2005; Scholz and Grabowiecki, 2007). These devices allow water to infiltrate through a range of hard surfaces including porous concrete and asphalt and non-porous block paving provided with infiltration channels of various designs, an example of which is shown in Figure 1. The underlying construction (traditionally a single-size aggregate subbase) is designed to store the stormwater and, either release it to the ground or, slowly discharge it to a drainage outlfall (attenuation).

(a) (b)

Figure 1: *(a) Part of the experimental pervious car park (consisting of pervious block paved and porous asphalt surfaces and both stone and plastic box storage elements) constructed under the candidate's direction in Coventry (from Newman, 2004b) and (b) the gas monitoring system (photograph by Tim Puehmeier).*

Whilst the benefits of reduced stormwater volume from such devices was easy to demonstrate, and the mechanisms easy to understand, it has taken a greater effort to illustrate the pollution removal properties. It has taken even more effort to develop the understanding of their physical, chemical and biological processes to the extent that these processes can be optimised. The benefits of PPS are now widely acknowledged (Brattebo and Booth, 2003; Pratt *et al*., 2002; Rushton, 2001). PPS operate by either attenuation or infiltration. In the infiltration mode they can compensate for groundwater recharge reduction caused by impervious surfaces (Klein, 1979; Simmons and Reynolds, 1982; Finkenbine *et al*., 2000) but this is not possible when receiving soils are impermeable or contaminated with undesirable leachable contaminants.

1.4.2 *Alternative Storage Elements*

The block paved PPS, with a geotextile between the laying course and the voided subbase-storage element, have been commercially available in the UK since 1995 and is now also installed in numerous countries. More recently the disadvantages of subbases constructed from primary aggregates (highly taxed and with limited void ratios (British Aggregates Association, 2005; Harrison *et al*., 2007; Thompson, 2004)) have been addressed by replacement of some or all of the subbase with plastic void forming units (often of recycled plastic). A particular version of these plastic void forming units (Permavoid®) has played a major role in many of the Outputs presented in this portfolio. It is unique in that it may be used very close to the surface, as shown in Figure 2 , a photograph of a section through the candidate's former experimental Permavoid®-based car park in Coventry. Whilst all plastic void forming units are capable of providing impressive void ratios and predictable flow regimes (Todorovic, 2003), only very strong units (Baker and Todorovic; 2004; Wilson 2002; 2008) can allow the installation of shallow pervious pavements e.g. in high water table or contaminated ground situations. The many weaker boxes on the market do not have the strength to support the required loadings unless covered with sufficient compacted material to spread the load over a wider area. The sustainability aspects of these systems were addressed in Puehmeier *et al.* (2004a).

Figure 2: *The candidate's Permavoid® based experimental car park in Coventry just prior to destructive testing (Newman 2004b)*

1.4.3 *Pollution Prevention with PPS*

As stormwater tends to be polluted (Botting and Bellette,1998; Stenstrom *et al*., 1984; Crabtree *et al*., 2006), there is a risk of surface or groundwater pollution when draining trafficked areas. Despite the expectation that leakage of oil from vehicles, as oil-seal technology improves (Smith *et al*., 1995), is reducing in importance, evidence shown in Figure 3 (taken January 2012, at a small railway station in Derbyshire) would seem to contradict this and regulators continue to consider oil pollution to be a threat from roads and paved parking areas. As well as concerns over small regular losses there are worries about the risk of a catastrophic failure of a sump or fuel tank. Effective PPS have been shown to remove the majority of pollutants present in stormwater runoff (Pratt *et al*., 2002; Rushton, 2001; Brattebo and Booth, 2003) but the limits to this, with respect to hydrocarbons, in an unimproved PPS have been illustrated (Newman *et al*., 2004a). This is discussed at Section 3.2.

Figure 3: *An example illustrating the fact that despite recent improvements in oil seal technology the loss of hydrocarbons onto car park surfaces can still be important (photographs taken by the candidate Jan. 2012, Whitwell Railway Station, Derbyshire).*

1.4.4 *Early PPS Research*

The first experimental PP of the Pratt design was constructed in 1986 as a car park (Pratt *et al*., 1989). The effluent from this attenuation system was monitored both for flow rate and limited water quality parameters. Very low suspended solids concentrations were measured in the outflow. The performance was in marked contrast to that found when monitoring highway gully outflows, where suspended solids concentrations vary greatly from tens to thousands of mg/l, both within and between rainfall events. Whilst no chemical analysis was carried out there was no (visibly) detectable release of hydrocarbons in the PPS effluent, despite it being apparent that spillages of oil had occurred (Pratt *et al.,*1995c). It was later established that, in the Pratt design, this was largely due to the oil retaining properties of the geotextile (Coupe *et al.,* 2006a).

This work was continued at Coventry University, initially concentrating on water quantity issues. It was the PhD programme undertaken by Brownstein that first addressed oil retention and biodegradation in a controlled experiment, marking the first involvement of the candidate with this area of research (having joined the team shortly after that programme of research started).

In this work a continuous gas monitoring system was used to monitor biodegradation in the test rig (by measuring elevation of CO_2 and depression of O_2) following a relatively large oil addition. It was possible to stimulate oil biodegradation using simple water soluble liquid inorganic fertilisers (chosen primarily to provide an appropriate ratio of nitrogen and phosphorus (around 5:1) and a commercially available oil degrading microbial assemblage (Pratt *et al.,* 1996) which the candidate had previously seen used in contaminated land applications and, importantly, was offered free of charge by the manufacturer.

This work did have some limitations. In this preliminary experiment a single pulse of oil was applied. Whilst the proportion of retained oil was, initially, very impressive, at the high loading used free product was always present in the effluent. Another issue was the fact that enhanced oil degradation was maintained for as little as 2 weeks before the respiration rates fell to such a level that his instrument could not detect a difference in sub-surface CO_2 from ambient concentrations. However, enhanced respiration could be re-established by the re-application of liquid fertiliser. It is likely that the carbon:major inorganic nutrient ratios were never optimal in the experiment as the degradation rate was seen to fall rapidly after a short period of time, possibly reflecting exhaustion of one or both of nitrogen or phosphorus.

This work by Brownstein also looked at temperature relations, demonstrating that, as expected, biodegradation in the PP fell to very low rates at temperatures below 8^{o}C. This illustrated the importance of effective, long term, retention of oil as the pavement would need to retain the oil without degradation throughout much of the winter period.

From here the work took several paths but the overall product of the research presented in this portfolio is a family of PPS which can, in response to a range of potential degrees of oil pollution and different user requirements, deal with both day to day inputs of pollutants, in terms of both oil retention and degradation but yet, where required, have the capability of retaining, in particular, catastrophic hydrocarbon losses from vehicles without significantly adding to cost, practical difficulties or problems of user acceptability.

The next chapter considers Outputs 1-3 which largely address oil retention and biodegradation in PPS which differ very little from the original Pratt design. The knowledge gained in producing these Outputs was fundamental to the design changes illustrated in subsequent chapters.

CHAPTER 2

OIL RETENTION AND DEGRADATION IN PPS

This chapter deals with three Outputs which address the following objectives:

a. Determine whether PPS are capable of maintaining complex, self sustaining, oil degrading, communities of microorganisms over extended periods and to identify the external inputs required to achieve this.
b. Develop a means by which required inorganic nutrients could be made available to the oil degrading microorganisms in a PP in a highly effective way whilst minimising losses of inorganic nutrients to ground or surface waters.

These outputs consist of two journal papers and one conference paper, of which the latter is a retrospective look at the work of the Coventry University PPS Research Group up to 2005.

2.1 Initial Investigations into Oil Biodegradation

2.1.1 *Slow Release Fertilisers and PPS*

Output 1 (Pratt *et al.,*1999) reports the first 100 days of an experiment which was later extended in Output 2 (Newman *et al.*, 2002a) to over 1300 days. It highlighted the ability of a slow release horticultural fertiliser (Osmocote, originally developed for oil biodegradation in response to the Exon Valdes disaster) to produce enhanced biodegradation of mineral oil over an extended period. The reported nitrogen and phosphorus ratios in the fertiliser seemed to indicate an almost 1:1 ratio. This probably represented an excess of phosphorus and indeed effluent concentrations of phosphorus were typically double that of nitrogen (Bond, 1999). The ratio of carbon to the nutrients was not constant as the concentration of oil in the system was periodically increasing because of the twice weekly addition of oil and the concentration of nutrients would be decreasing with time as the fertilizer pellets were depleted. Because of the unpredictability of carbon inputs in real situations it would probably be impossible to ensure that carbon/nutrient ratios were optimised. This would be compounded by the physical nature of the system since the bulk of the hydrocarbon would always be in a separate phase unless oleophilic fertilisers were used and the use of these could lead to mobilisation of the oil and loss from the structure.

This experiment also indicated the high proportion of oil retained in the PP when challenged with lubricating oil added, intermittently (but not continuously) at a rate which was reasonably close to the expected daily input to a car park (as established by Bond (1999)). Output 1 has become widely cited in official and semi-official guidance on SUDS/LID (e.g. Hinman, 2005; South East Michigan Council of Governments, 2008; Oregon Environmental Council, 2007; Low Impact Development Centre/Southern California Stormwater Monitoring Coalition, 2010)(see also Appendix 3).

2.1.2 *Beyond a "Black Box" Approach*

Despite the widely expressed recognition of the importance of the results produced by the experiments reported in Output 1, the approach taken was not without external criticism. The most significant was when the work was described by a delegate at a conference in 1998 as "a black box approach" with the implication that it concentrated too much on outcomes and lacked fundamental understanding (J. Crosnier – comments made during discussion session at the 12^{th} European Junior Workshop on Runoff Pollution and Stormwater Infiltration, Nantes, France, 12-15 March 1998). Output 2 was selected as being representative of the next phase of the work and Output 3 (Newman *et al.,* 2006a) is a retrospective review paper which brought together many of the important related areas of development in the field of PPS microbiology. In part, the work which resulted in Outputs 2 and 3 formed a response to the "black box" criticism. Whilst Output 1 (and previous publications by the Coventry University PPS Group (Pratt *et al.,* 1996; Newman *et al*., 1998)) had concentrated on how well the PPS could perform as an oil-biodegrading system rather than how it was achieving that level of performance. There was, at that time, no other group working on the oil retention and biodegradation issues in controlled laboratory conditions. This was possibly due to the relative difficulty in measuring hydrocarbons when compared to the relative ease of measurement of metals by atomic spectrometry, which was and is a common area of study (Legret *et al*., 1994; 2004; Legret and Colandini, 1999).

2.2 Microbial Ecology of Pervious Pavement Systems

In relation to the microbiology of the PPS, the most closely related body of previous work had been carried out on the microbiology of sewage treatment filter beds (e.g. Woombs and Laybourn-Parry, 1986; Rowan *et al.,* 2003). Parallels are often drawn with filter beds because of the voided stone PPS subbase, over which polluted water trickles but this is rather tenuous since filter beds differ very markedly from the

PPS in that they are continuously wetted and are rarely faced with degradation of separate phase hydrocarbons. Thus the studies presented in Output 2 represent some important first steps in the understanding of the microbial ecology of the PPS. The research described in this paper had a specific objective of assessing the nature and biodiversity of the microbial fauna found within the PPS after four years of near-continuous oil and simulated rain inputs.

2.2.1 *The Need to Inoculate*

One of the important questions that needed to be answered was whether the biodegradation process required initiation by the addition of oil degrading microbial communities at the outset or whether microorganisms could, in a short timeframe, be recruited either from the pavement materials themselves or from external environmental inputs. This question had been raised in a wider context by Pritchard (1994). The work reported in Outputs 2 and 3 contributed significantly to the recognition that a commercially obtained oil degrading, microbial mixture was not significantly better at degrading oil than the indigenous microbial biomass established within the pavement. The work reported in Output 2 concentrated largely on the eukaryotic portion of the microbial communities, the first attempt to study the eukaryotic communities within a PPS. However, these studies were accompanied by parallel works in which a detailed study of the prokaryotic fraction was made. This was originally reported as Newman *et al.,* (2001; 2002b) but Output 3, being largely a review paper, also presents, amongst other very important data, the most significant results of the molecular studies on prokaryotic PPS communities.

2.2.2 *Molecular Approach*

This research was one of the first applications of molecular methods in the study of the microbiology of any SuDS system. In this project the Polymerase Chain Reaction (PCR) (Arnheim and Erlich, 1992) was used to amplify selected parts of DNA extracted from cells present in the effluent generated by the long term test rig (which was also studied in Output 1). Denaturing Gradient Gel Electrophoresis (DGGE) (Myers *et al*., 1987; Giovannoni *et al.,* 1990; Sheffield *et al.,* 1989) was used in conjunction with PCR to target part of the 16S ribosomal RNA genes (Ferris *et al.,* 1996 ; Miller *et al.,*1999; Muyzer *et al.,*1993; Muyzer and de Waal, 1994; de Lipthaya, 2004) from cells collected from the effluent from the test rig and from the original inoculum. This experiment showed that the long term PPS model and initial inoculum produced significantly different banding patterns which confirmed that over time the communities within the porous pavement changes and the initial inoculum appears to be out-competed by organisms from the environment. This work was highly dependent on that previously reported in Output 1, since the effluent feedstock used for the collection of DNA was the same long term model. Whilst this molecular work on the prokaryotic communities strongly backed up the conclusion that an addition of oil degrading inoculum was not essential for the functioning of the PPS, one should not necessarily conclude that advantage of an inoculum could never accrue. Indeed the addition of a seed from an established oil-degrading test rig has been a common feature of many investigations as a means of reducing the lag period in experiments.

2.2.3 *Biofilm Structure and Activity*

Developing an understanding of the structure and arrangement of the oil degrading biofilm in relation to the oil retaining geotextile was also an important aim of the work underway at this time. Both optical and electron microscopy were used to monitor biofilm development, and also confirmed, in a highly visual way, that the geotextile within the pavement could quickly develop a complex community structure with high biodiversity (see Figures 1 and 2 of Output 2). In this part of the study samples for analysis by scanning electron microscopy (SEM) were obtained by embedding SEM stubs directly into the geotextile layer with geotextile fabric stretched across their surface. The novel arrangement of the stub was later reported more fully in a paper which reviewed the efforts made to study the PPS by electron microscopy (Coupe *et al*., 2006b). The results demonstrated that the large and diverse microbial communities found in the rigs were utilising the oil supplied, in conjunction with added inorganic nutrients. The effluent's viable bacterial count (using nutrient agar dilution plates) was around 10^4/ml in both inoculated and non-inoculated systems and the amount of oil retained on the rig materials were similar. In both, diverse and abundant protozoan and metazoan communities had been established.

2.2.4 *Response to Changing Conditions*

Output 2 also reported the ongoing long term performance of the large PPS, which had continued to perform well despite the relatively consistent oil application over a 4-year period. The speed at which the microbial biofilm was able to respond to changed conditions demonstrated considerable resilience. An 8-month decline in the nutrient status was reversed within 48 hours once an application of fresh Osmocote Plus (Osmocote with added trace elements) was provided. A similar response was seen after a 75-day period of imposed drought.

It had been proposed earlier (Newman *et al.,* 2001) that more complex microbial communities in the PPS would be both more stable under conditions of stress and capable of the most effective utilisation of resources. This was not a universally accepted proposal (Pimm,1984) but if this was the case, then a quantitative measure of microbial biodiversity would be a useful factor in optimising the system. It was also anticipated that, additionally, this would also provide an essential tool in more theoretical studies.

2.2.5 *Further Microbial Diversity Studies*

As mentioned at 2.2.1, Output 2 focussed upon the diversity of the eukaryotic fraction of the microbial assemblage, concentrating mainly on protozoa but also including microscopic multi-cellular organisms. Whilst these predatory eukaryotic organisms were felt to be very important to the health of the oil degrading ecosystem, they are not oil degrading in themselves but depend on grazing the oil degrading organisms which utilize the oil as their source of carbon and energy. It was believed that the regulating effect of predators on the saprophytic members of the biofilm was particularly important. It is possible that, where the protozoan and metazoan communities form a dense, species-rich biofilm, they may stimulate the bio-degradation process. This was investigated in a later collaborative piece of work (Coupe *et al.,* 2003) which drew heavily from Output 2. This showed that biodegradation was facilitated to a similar degree by bacteria or fungi, (as demonstrated by inhibition with tetracycline and cycloheximide respectively) but that the presence of protozoa, in combination with either bacteria, fungi or both, showed a positive effect on oil degradation. It was suggested that recycling of inorganic nutrients by protozoan predation was an important factor, as indicated by earlier work by Kahlert and Baunsgaard (1999). This later paper also contradicted the idea that predation on bacteria and fungi, as suggested by other workers, would lead to a decrease in oil utilisation (Darbyshire, 1994 ; Huang *et al.,* 1981; Pussard, 1994). From a practical point of view the initial impact of these microbial diversity studies impacted more on the way in which the PPS research group looked at measuring the microbiological health of the system (addressed at section 2.2.6) than in providing a direct tool for modifying the way the PPS was managed. It must be remembered that the initial design of the PP was never done with biodegradation in mind. It also provided those involved with the confidence that the Pratt design of the PP , based mainly on the needs of water attenuation properties, was , coincidentally, also capable of providing at least , an adequate environment for what seemed to be a complex ecosystem.

2.2.6 *A Measure of Microbiological "Health" of the PPS*

As well as the intended outcomes of the work reported in Output 2 another important conclusion was established. This was that the microscopic approach, using protozoa as a surrogate for overall biodiversity, was a much more practicable approach to the measurement of "ecosystem health" than the molecular approach using

PCR and DGGE which had been embarked upon in an effort to produce a numerical index which would be more acceptable to the engineering community which was the intended audience of the outputs. This conclusion was based on the fact that the molecular methods produce less information in a much longer time and is highly dependent on high capital investment, high running costs and on the resources available for training. Whilst this might be obvious in hindsight it is pertinent that the candidate initially approached the problem with a microbial genetics education which pre-dated the development of the PCR reaction as an amplification tool. The microscopic method, on the other hand, was found to be relatively easy to cascade to other members of the research group and, subsequently, it was used on several occasions (e.g. Spicer, 2006; Nnadi, 2009), whilst the further use of molecular methods was limited (Puehmeier *et al*., 2005). Outputs 1 and 2 continued to be the basis of significant ongoing work through to the middle of the first decade of the 21st century.

2.3 Limitations and Responses

It has been pointed out by others that the work reported in Outputs 1-3 (and the other works cited above) were laboratory experiments carried out in an idealised environment. Indeed an important criticism of the work reported in Outputs 1 and 2 (and subsequent works) would be that the oil additions were low and additive and that heavier loadings, or continual rather than intermittent inputs were not addressed. However, from the results of these laboratory based experiments a series of field experiments were developed which at least addressed the higher loadings (again as one off additions rather than continuous flows, reflecting the real nature of catastrophic losses of lubricants from vehicles) (Newman *et al.,* 2004a). The outdoor experiments are discussed further in section 3.2 below but it is important to note here that they resulted in the recognition that the traditional porous car parking surface would not be suitable in high risk situations. This inspired the invention of a system which incorporates a gravity separator in the subbase. This invention is the subject of Output 4 and is considered in Chapter 3.

CHAPTER 3

INCORPORATING A GRAVITY SEPARATOR INTO A PERVIOUS PAVEMENT

This chapter addresses objective c:

> *Study the response of traditional PPS to catastrophic vehicle oil losses and explore a practical system to allow the use of the PPS in highly sensitive environments or high oil spill-risk areas*.

It does so by providing an overview of the combination of two journal papers and a patent, which together represent the invention which constitutes Output 4 of which the candidate was the sole inventor. This invention is a modified PPS capable of dealing with large oil spills from vehicles in situations where the consequences of a spill would be significant.

3.1 Background

Output 4 is represented in the portfolio by a combination of a patent (for a device which the candidate was the sole inventor (Newman, 2002)), a journal article (which includes two experiments which illustrate clearly the need for the device (Newman *et al*., 2004a)) and a journal article which reports an experiment in which the performance of the finished product is illustrated (Wilson *et al.,* 2003). The device was intended to allow the benefits of gravity separator to be intimately linked to those of a PP. Its intended application is under particular parking areas where the risk of a large spillage is high or where the environmental consequences of an escape of hydrocarbons would be unacceptable. It will be shown later that the Permaceptor®, the trade name under which this device has been marketed, is now finding applications in other areas and indeed has seen its greatest success in a very specialist area. It will also become clear that the principle of a very shallow, and widely dispersed, gravity separator was an important principle leading to a significant component constituting part of Output 5.

3.2 Limitations on Oil Retention in PPS

There are limitations in the capability of PPS to retain oil. The ongoing experiments mentioned above took place around the time that the Permaceptor® was invented and these involved three types of full scale experimental car park. One system (consisting of two duplicate units with block paved surfaces) was constructed with a stone subbase and two further systems were constructed with plastic subbase replacement units (one with a block paved surface and one with a porous asphalt surface). The car parks were all equipped with water sample collection pits and a common gas monitoring kiosk (drawing air from the subbases via a switchable manifold system (see Figure 1(b)) had been installed. These experimental car parks had been operated for over 2 years with regular grab sampling during rain events and no significant hydrocarbons had been measured in the effluent stream. When it became clear that these experimental car parks were to be lost to the research group an experiment was devised (reported in Newman *et al.,* 2004a) which involved simulating the total loss of oil from the sump of a large car. This experiment was one that has not been carried out by any other workers. As the car parks were shortly to be excavated, this allowed the deliberate oil dosing of the car park surface in a real, live car park situation. The results are summarised in the graph shown in Figure 4 (Figure 5 in the paper itself). After about 22 hours the concentration of oil in the effluent had exceeded 8000 mg/l (including a significant amount of free product). Clearly, the oil retaining capabilities of the pervious pavement had been overcome and the case for a means of retaining the oil that could be released in a major pollution event was clearly established.

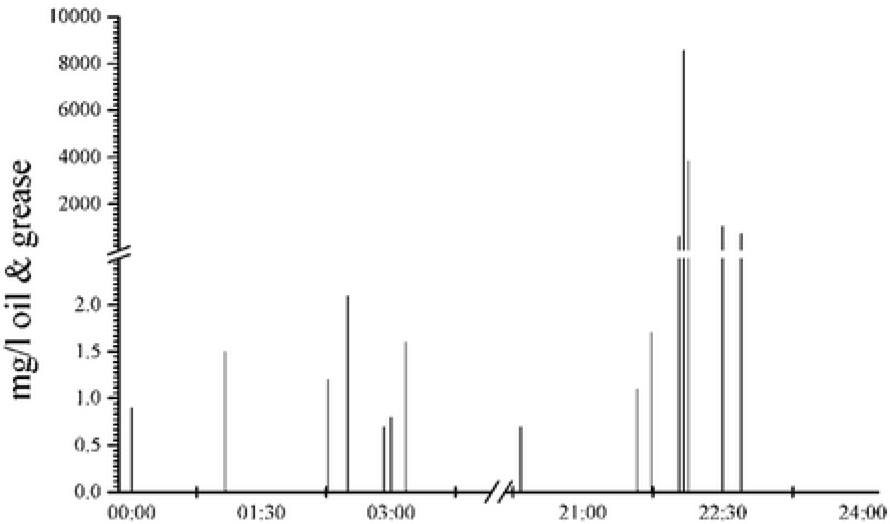

Figure 4: *Results from shock oil loading experiment (15 litres on 4 bay car park) on PPS (from Newman et al, 2004a) Copyright Geological Society reproduced with permission.*

Further work, which confirmed this problem, was also reported in Newman *et al* (2004a). These were laboratory scale experiments aimed at comparing the Permaceptor® concept to the original Pratt concept. The reader is directed to Figure 7 of the paper which shows the experimental set up, a novel design which, because of its very low cost and ease of producing replicated experiments, became a well established model system within the Coventry University group for several years. The reader is also directed to Table 1 of the paper which shows that the Pratt design is very easily overloaded and that in high loading situations the Permaceptor® model released over 2000 times less oil in the experimental period than the model based on the Pratt cross section.

3.3 The Permaceptor®

The Permaceptor® is essentially a shallow, but extensive, gravity separator which is constructed directly beneath the laying course of a PP. It was conceived as being constructed using either stone subbase or plastic box based storage layers. The principle is that any free product that passes the primary retention layer (the geotextile) will be stilled by the low velocity of water within the system and will float on the permanent pool of water. Low velocity interactions, either directly between oil droplets or on either the aggregate or the support struts in the plastic boxes, help to increase the particle buoyancy. It is important to recognise here that saturation of the geotextile would only occur locally, very close to the spill and that in the Permaceptor® even a large volume of spilled oil will spread to a very thin layer on top of the water body. This is illustrated by Figure 5 which was extracted from Wilson *et al.* (2003) and is reproduced for the convenience of the reader.

3.3.1 *Behaviour of Oil in the Permaceptor®*

Although examination of the patent (Newman, 2002) should reveal that it is capable of bringing major benefits when the pervious pavement system is used in a direct infiltration mode, it should also be evident that the greatest advantage of the Permaceptor® accrues when used in its attenuation mode. In this situation it is possible to obstruct the outflow from the outlet pipe and allow the system to flood to the level of the laying course. This would cause the free product to rise through the geotextile and laying course where it would allow its retention (now in the form of a thin layer) by smearing on the geotextile fibres and hold it in a damp yet aerobic environment to encourage biodegradation. Wilson *et al.* (2003) also demonstrated the excellent oil retaining capability of the Permaceptor® under high rainfall conditions. Clearly the experimental approach had to be modified considerably from the standard test for oil interceptors (BSI, 2002) but the system was tested to a similar degree of challenge (See Table 1 in the paper). It was clear that the floating oil layer was not disturbed even when subject to very high simulated rainfall intensities. The work showed that the system has limitations when exposed to detergents used in the cleaning of motor vehicles. This has important consequences for the management of these systems, particularly following major oil releases. The ability of the Permaceptor® to allow the rapid evacuation of the entire liquid contents with, for example, a gully sucker, following a major oil spill is a major advantage of this invention.

Figure removed due to lack of copyright permission.

Figure 5: *Behaviour of clean oil in a "Permaceptor®" after application of detergent (Wilson et al., 2003)*

Subsequently, the glass sided channel used to produce the data for this paper was also used to demonstrate the predictable flow characteristics of the system when constructed with Permavoid® subbase replacement boxes Studies on the microbiology of the system were also reported (Newman *et al.,* 2004b).

3.3.2 *Large Scale Experimental Systems*

Subsequent studies have been carried out, including a considerable amount of unpublished in-house testing (which formed part of the KTP scheme which funded the validation work). This has included a long term outdoor experiment based on the extensive test bed system constructed in Bury to replace the Coventry experimental car parks depicted in Figures 1 and 2. In this experiment a perviously paved single parking bay was constructed such that the outlet pipe formed a water trap (essentially forming an alternative method of constructing the Permaceptor® system). It was challenged by the addition of 15 litres of used engine oil, followed two weeks later by 15 litres of diesel, with large storm simulations at each dosing event followed by natural rainfall over the experimental period. The system was monitored for hydrocarbons and over 2 months the maximum TPH measure was always less than 5mg/l and the system continued to be visually monitored for free product for over 12 months. Throughout that time there was no free product detected. When the system was dismantled a body of free product was, as expected, found floating in a thin layer on top of the permanent pool of water maintained in the trap. A more conventional design of Permaceptor®, built within the same structure (Figure 6), which did not have any artificial hydrocarbon applications but has been subject to actual day to day oil losses for over 6 years, continues to release effluent totally free of free phase oil.

3.4 Applications

Despite being intended for general applications within PPS installations, the Permaceptor® has found its most popular application in a specialist niche. This is as a temporary plant refuelling stand for use on construction sites (Culleton *et al.,* 2005) and has also been developed as an additional miniaturised oil interception device intended to be utilised under traditional hard paved surfaces served by gulley pots draining very small catchments. This device is marketed under the name GullyCeptor (Newman and Puehmeier, 2008). However, the commercial uptake of the Permaceptor® based PPS, in the form that it was originally envisaged, has been less than had been anticipated. The failure of the Permaceptor® to make the commercial impact that might have been expected is due to two factors. The first of these is the subsequent development of advanced geotextiles (Puehmeier and

Newman, 2008; Newman *et al.,* 2006b) which significantly reduced the need for the Permaceptor®.

Figure 6: The experimental Permaceptor test beds constructed in Bury (Newman, 2004b).

The second is a particular criticism based on the practicality of it being adopted over large areas of car park. The system is entirely dependent on maintaining a pool of water within it and, thus, in the absolute integrity of the membrane used to line the system. This is very difficult (and expensive) when applied on a large car park where welded seams in the underlying membrane will be required. This problem was overcome by a new development (discussed in Chapter 4), an alternative shallow gravity separation system which was not dependent on membrane integrity for its ability to remove hydrocarbons i.e. Output 5.

CHAPTER 4

A PRACTICAL

MACRO-PERVIOUS PAVEMENT SYSTEM

This chapter provides an overview to Output 5 which consists of an intimately linked pair of inventions, represented in the portfolio by two patents (Newman, 2004; & Shuttleworth *et al.,* 2005) and a conference paper which outlines a small part of the development and validation work which has been undertaken on both devices (Puehmeier *et al.,* 2005). Also included is a link to a video clip which is provided to illustrate how the two devices work together as a system. The inventions constitute essential components of a macro-pervious pavement system which is an alternative system and can provide the properties of a PPS in situations when the end user rejects a paved area with a pervious surface. It thus addresses the following objective:

> *Establish a practical approach to the use of pervious subbases in the absence of a pervious surface where developer resistance is leaning towards positive drainage because of mistrust of the pervious surfaces available.*

4.1 Background

4.1.1 *Alternatives to a PPS*

The term macro-pervious pavement system (MPPS), first coined at the EWRI conference in the USA in 2011 (Newman *et al.,* 2011b), describes a system forming a sub-class of pervious pavements, where the vast majority of the surface is impermeable. Whilst the candidate does not claim credit either for the concept of the MPPS (forms of this were proposed (under a different name) much earlier e.g. Raimbault, 1993) or the detailed designs of the currently marketed system (this is the work of designers at SEL Environmental and EPG Ltd). However, it is the combination of the two patented devices included in Output 5 that has enabled a MPPS, with pollution retaining capabilities equivalent to a standard PPS, to become a practical proposition. The candidate claims full credit for one and a fundamental role in the development of the other.

Provided there is sufficient transmission capacity to direct stormwater underground sufficiently quickly to prevent flooding during the design storm, there is no reason why the total infiltration capacity of a PPS surface cannot be agglomerated into a collection of distinct, but relatively isolated, infiltration points. These isolated water infiltration points could take many forms, such as discrete holes provided with grids (as in Raimbault,1993), or in the form adopted by the candidate and his co-workers, an extensive network of modified channel drains which discharge into the subbase zone. The devices included in Output 5 represent major steps in the evolution of the application of the SUDS philosophy to the drainage of hard paved parking areas.

4.1.2 *The Need for the MPPS*

Traditional pervious pavements offer clear environmental benefits, particularly as a means of incorporating a highly efficient stormwater treatment system very close to the source of pollutants. Why are they not universally adopted in new builds? The candidate believes that this is because specifiers fear that the traditional pervious surfaces, either block paved surfaces or porous asphalt, have reduced longevity or suffer from a poor level of performance (for example, a tendency to clog or the need to use specialised surface cleaning processes (e.g. Dierkes *et al.,* 2002)).

These fears are often unfounded and Gill (2011), in an article aimed at local authority engineers, summarised the uptake problem very well:

"It appears that many people prefer the tried and tested approaches of the past even when new understanding offers enlightenment"

It became clear that a system was required that would provide all of the benefits of a traditional pervious pavement, within a system which allowed the use of traditional asphalt (or poured concrete) surfacing. The system would need a means to direct the water underground, a temporary water storage element and, as far as possible, a substitute for the several layers of water treatment provided by the multi-layered structure of the pervious pavement. It was also seen as advantageous if the pollutants could be trapped as early in the treatment train as possible and in such a way that maintenance issues do not become a barrier to adoption.

4.2 Directing the Water Underground

The first requirement was to direct stormwater underground whilst providing an initial treatment process involving removal of hydrocarbons and suspended solids (and the micro-pollutants associated with them). This resulted in the development of the **oil separating channel drain** (OSCD) (Shuttleworth *et al.,* 2005; patent).

4.2.1 *Origins*

The first thing to note for this device is that its development owed much to Output 4. Like the Permaceptor® it incorporates a near-surface gravity separator which is relatively shallow and, unlike a traditional linear channel drain, serves a very limited catchment area per unit length.

4.2.2 *Initial Problems*

Traditional channel drains are designed to conduct water, not to retain it, and, in normal use, a slight leakage from the joints during rain events is not considered to be a problem. However, in practice, when these devices were investigated as oil separating devices constructing the joints required significant extra effort to obtain reliable joint integrity. A solution was sought that did not rely on the grouting of drain channel sections to maintain the integrity of the water trap.

4.2.3 *Ongoing Development*

The solution was a channel drain in which the oil separating system was placed at each end of the channel with the port for the outlet pipe being formed as the two consecutive channels are brought together (Figure 8). Maintenance of a water seal is never dependent on the seal between two channel sections.

This is shown clearly in a video sequence available on U-tube (http://www.youtube.com/watch?v=kGTw6Xmg6ik)

4.2.4 *Further Innovation*

Figure 7 should be self explanatory and further description is not given except that neither Figure 7 or the video mentioned above does makes clear the role of the “cover lids” used to prevent contaminated water from entering the post-baffle zone of the system. The redesigned channel drain was subjected to testing and it was found necessary to introduce modified cover plates as shown in the video clip.

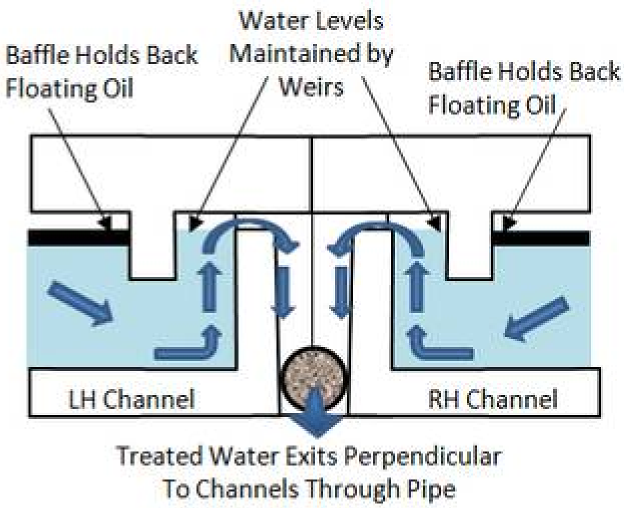

Figure 7: *Cross Section through Separator Section during Wet Weather*

The role of these modified plates was to redirect the water flows such that any entrained droplets were driven away from the baffle plate at each end of the channel section, with the two flows of water arranged to meet at the centre, driving the turbulent flows upwards and causing the droplet to re-interact with the floating hydrocarbon layer. The exact angles and lengths of the new deflection plates were determined experimentally.

The empirical approach to determination of the required length and angle of the "wings" used to redirect the water could be criticised as there is a growing tendency to apply the techniques of computational fluid dynamics to similar problems (Faram *et al.,* 2005, Andoh *et al.,* 2008). However the candidate is content that, in practice, it is unlikely to have produced any practical improvement.

The initial validation experiments for the OSCD are reported in Puehmeier *et al*. (2005). The results indicated that the oil separating channel drain released water of very high quality (with respect to hydrocarbons) (see Table 1 *op.cit*.). The OSCD (which also forms a preliminary silt trap) provides the required mechanism for directing water underground whilst acting as a preliminary pollution collection device. The most significant application for the device has been as part of the MPPS but there are other potential applications (Culleton *et al*., 2005).

4.3 A Second Component: The Floating Mat Device

4.3.1 *Origins of the Floating Mat Device*

A second important component in the MPPS treatment train is the floating mat device (FMD) (Newman, 2004). The original concept of the FMD was to apply it to the entire surface area of pervious pavements which utilised the Permavoid® subbase replacement unit. The intention was to substitute for the greater surface area that is available in stone subbase systems when compared to plastic box type systems. The original idea was that within a PP equipped with a plastic box storage element the polypropylene mat would float during rain events, trap floating oil and then fall to the base of the highly voided unit where it would remain damp under aerobic conditions which would encourage biodegradation. Its development took place alongside that of the Permaceptor®. If used in this system the mat would continuously float on the permanent pool of water, holding the oil in the aerobic zone and adjacent to the oil degrading biofilm. However, when used as part of the MPPS a limited number of these devices are placed directly downstream of the outlets from the OSCD system with an interface provided by a simple diffuser to disperse the kinetic energy of the flowing water. The principle of the FMD is that, within a stilled water body, droplets of free product hydrocarbons will float to the surface and if they collide with a floating mat of a suitable material they will interact with it and be trapped long enough to allow a biodegradation process to take place. Without this device the MPPS might never have been considered by regulators to provide sufficient levels of treatment for it to be acceptable as a replacement for a PP system.

Originally the development work on this device was carried out using geotextiles tacked to both sides of a floating, semi-rigid, plastic grid consisting of polyethylene which had been made buoyant by the incorporation of a blowing agent (Figure 8). Neither the patent, or indeed any published reports, make clear the extensive period of development that this component required. The availability of CNC laser cutting facilities within Coventry University was fundamental to the work as numerous prototypes were produced whilst optimising the competing needs of maximising both vertical movement within the box and surface area available for oil entrapment and biodegradation.

4.3.3 *Validation and Further Research*

In a MPPS, although the majority of oil will be retained by the channel drain, any small amounts of oil escaping the system will readily interact with the floating mat. The accumulation of oil in the channel drain and the provision of inorganic nutrients through the accumulation of materials, such as leaves and animal excreta, would provide large numbers of microorganisms to seed the floating mat and provide a stable biofilm. One of the criticisms of the work on this device to date is that this aspect of the microbiology has not yet been fully investigated. The microbiology and biochemistry of the FMD has not been totally ignored. In addition to providing validation data on the prototype channel drain, Puehmeier *et al.,* (2005) describes molecular biological studies and SEM studies on FMDs. However, these molecular studies could be seen to be only partially complete since they were only based on the use of PCR and DGGE (without any attempt to sequence them).


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Figure 8*: Cross section of FMD prototype mat showing laser cut holes to allow penetration of Permavoid® box support struts (Puehmeier, 2009 reproduced with permission)*

That paper also reports an assessment of the adenosine triphosphate (ATP) content as a measure of active biomass using the luminescence method adopted by Ocio and Brookes (1990). The ATP studies showed that in situations without significant addition of nutrients the activity of the biofilm formed was around 1/30 of that for a fertilised system.

Puehmeier *et al.,* (2005) also addressed a question which had been raised several times in relation to biodegradation studies carried out using clean mineral oil. This was whether or not toxic or bacteriostatic components in used oil would inhibit biodegradation. As can be seen from this paper, at least as far as a floating mat-equipped PPS is concerned, the degradation rate of used oil was actually higher than that for clean mineral oil. The availability of nitrogen compounds generated by oxidation of atmospheric nitrogen within the combustion chamber is a possible reason for this. A similar conclusion was reached in independent work by Coupe *et al*., (2005).

4.4 Combining the Devices into a System

4.4.1 *The plastic box-based MPPS*

The two patents and the accompanying papers, which are submitted as Output 5, have illustrated the effectiveness of the two novel components, the OSCD and the FMD. The way in which these two devices work together to form a macro-pervious pavement is well illustrated by the video clip mentioned previously.

4.4.2 *The Hybrid Subbase System*

An alternative approach, developed by SEL Environmental Ltd and their partners, replaced much of the Permavoid® box storage capacity with voids provided by graded stone. This hybrid subbase MPPS replaces a large volume of the sub-surface storage void with a porous granular material. Regulatory concerns are addressed by introducing a greater surface area for sorption and biodegradation downstream of the point of water ingress. Furthermore, this is in combination with an easily cleanable upstream separator which will retain severe spills long enough for them to be retrieved from the system without contaminating the downstream components, impossible with a traditional PPS.

However the use of the stone subbase sacrifices void ratio and results in requirement for deeper excavation to achieve the correct attenuation volume because of the lower void ratio of the aggregate layer.

Overall this Chapter has highlighted the further development of gravity separation incorporated within a sub-set of PPS. The next chapter moves away from the retention mechanism and re-addresses the important role of biodegradation of hydrocarbons within the whole family of PP devices.

CHAPTER 5

ENHANCED GEOTEXTILES FOR PPS APPLICATIONS

The following objective is addressed in this chapter through the medium of an overview of Output 6:

> *Develop a means by which required inorganic nutrients could be made available to the oil degrading microorganisms in a PP in a highly effective way whilst minimising losses of inorganic nutrients to ground or surface waters.*

Output 6 is a journal paper which outlines the development of a geotextile which incorporates a mechanism for the release of a key inorganic nutrient directly at the point within a PPS that oil is retained and where the majority of oil degrading biofilm develops.

5.1 Geotextiles in Pervious Pavements

5.1.1 *The Geotextile/no Geotextile Debate*

As mentioned at section 1.3.3 the most commonly used pervious pavement system in the UK is based on a design by Pratt (Pratt, 1990;1996; Pratt, *et al.,* 1995b) which uses a geotextile to separate the storage layer (uniform sized stone of around 50mm) from a laying course of stone with a size which can range from 5-10mm. In a 78 day experiment (using a single application of oil) (Bond 1999), which used identical apparatus to that presented as Figure 1 in Output 3, approximately 31% of applied oil was degraded, 1% was lost in the effluent and 49% was trapped on the geotextile. The remainder was retained in other parts of the system.

Whilst this data illustrates the importance of the geotextile in the retention role the use of geotextiles to separate the laying course from the storage/load bearing layer does not have universal agreement. It has been proposed that it can produce a slip plane within the structure (e.g. Dept. of Planning and Local Government, 2010) and, furthermore, a recent paper produced results which conflicted somewhat with the oil retention advantages proposed by the Coventry University group (Mullaney, 2011). However, in a stone subbase system, without the separating effect of the geotextile, there would need to be a carefully graded subbase to prevent loss of the laying course material into the open graded storage layer (Omoto *et al.,* 2003). The required fines utilised to create this graded transition may have an enhanced effect on hydrocarbon retention in a geotextile-free PPS but this would be at the expense of reduced storage volume. Where “plastic boxes” are used directly below the laying course a separating geotextile is mandatory as the loss of laying course material into the boxes could not otherwise be avoided.

5.1.2 *Benefits of the Geotextile*

Whilst the "geotextile/no geotextile" debate will, no doubt, be the subject of controversy for some time there are clear environmental benefits in using the upper geotextile since the retention of hydrocarbons in the upper parts of the structure has several advantages:

1) Contamination is restricted to the upper layers of the system making the recycling of the subbase aggregate, after the working life of the pavement, a much easier prospect. It would certainly reduce the volume of contaminated waste to be dealt with.
2) Retaining the oil in the upper layers of the pavement cross section enhances biodegradation since it is always held in the most aerobic part of the system and in the summer months, when most of the biodegradation will take place, it is maintained at a slightly higher temperature due to insolation effects (Novo, *et al.,* 2010).
3) As oil is not allowed to form anaerobic flocks at the waterlogged base of the structure it will not contribute to the generation of either methane or dintrogen oxide, two very potent greenhouse gases (as mentioned in Output 3, the candidate has measured trace methane emissions from PPS).
4) Optical and electron microscope studies have illustrated that the geotextile constitutes an excellent surface for the development of biofilm. The geotextile can be further modified to enhance these properties.

5.2 Modified Geotextiles

5.2.1 *Performance Enhancements in Geotextiles*

A major theme in the research illustrated by this portfolio has been the **retention** of hydrocarbons in PPS structures. In 2004 the candidate was one of 3 inventors on a patent application for a novel geotextile with enhanced hydrocarbon retention capabilities (Newman *et al.,* 2006c). The limitation on the number of outputs permitted to be included in this portfolio has precluded the selection of this patent as one of the included Outputs but it is important to note that within the patent is the following sentence (p.5, lines 24-29):

".... *further materials may be provided for a purpose other than those of the hydrophobic materials and the hydrophilic material e.g. one or more materials may be provided as nutrients for the biofilm.*"

Clearly, the patent anticipates the capability of incorporating nutrients into the geotextile itself but to date the enhanced oil retention properties (brought about by additives aimed at manipulating the polarity of the fibres surfaces) have not been combined with the provision of nutrients. However, considerable work has been done on incorporating nutrient additives within otherwise unmodified geotextile fibres with the aim of combining the two at some stage in the future. Output 6 (Newman *et al.,* 2011a) is an abridged version of a paper originally published in the 2010 Novatec proceedings (Newman *et al*., 2010). This Output illustrates the efforts that have been made to respond to the need to provide inorganic nutrients to oil degrading microorganisms in a PP. Previous work had shown that the geotextile was the site of oil deposition in those pavements provided with a suitable geotextile (e.g. Output 3 and Newman *et al.,* 2006b). It had also been shown that horticultural slow release fertiliser was an effective material for providing the inorganic nutrients they required and that they could provide inorganic nutrients without reapplication for periods of over a year (Outputs 1, 2 and 3).

The Osmocote slow release fertiliser pellets which were used by several researchers in the Coventry University PPS group to provide enhanced oil degradation rates in their test rigs over many years, but have rarely been used in full scale live car parking situations. Concerns had been raised as to the potential for these slow release fertiliser pellets to release nutrients in excess and their use was never promoted by environmental regulators, despite the proven advantages in relation to oil degradation. The fears relating to excess nutrient release has subsequently been confirmed spectacularly in the work of Nnadi *et al.,* (2008) which showed that the nutrients released were in sufficient concentrations and at suitable ratios to be used to enhance the growth of both tomato and ryegrass, a clear indication of the potential to cause eutrophication. Information from work carried out within the research group indicated that P and not N was the limiting nutrient (Coupe, 2004; Jenkins, 2002). This was not totally unexpected since atmospheric inputs of nitrogen containing compounds were far more likely. For example, Sauer *et al.,* (2008) estimates that typically 10% and up to 32% of inputs of oxidised nitrogen into agricultural soils came from atmospheric sources. Additionally, inputs from bird and mammal excreta and via soils brought in on vehicle wheels would be expected to contribute N to the system.

5.3.1 *Incorporating Nutrients into the Textile*

As indicated above, the ability to incorporate nutrients directly into the geotextile was envisaged in the 2006 patent (Newman *et al.,* 2006c). Work was started in 2002, well before the patent application, on the means by which this might be achieved. In response to the information available and following discussions with a polymer additive supplier a successful application for an EPSRC Industrial CASE award was made by the candidate. This resulted in the PhD programme carried out by Gillian Spicer under the supervision of the candidate and Dr D. Lynch. This programme focussed on organic micro-beads (which had previously been invented by Lynch and for which the University held the IPR). These beads were known to sorb inorganic compounds and, in a later publication, beads which had been loaded with ammonium phosphate were used in a masterbatch to spin fibres of polypropylene (Spicer *et al.,* 2006).

Clearly this work built on the firm foundation established during research which resulted in Outputs 1-3 and, in turn, the work became the basis upon which Output 6 was progressed. Output 6 reviews the earlier work (Spicer *et al.,* 2006) and points out that, despite success in showing enhanced oil biodegradation, this additive was never adopted by the manufacturer as a practical approach because of cost, availability and fibre breakage issues. With this in mind a new approach was sought and, with the aid of Addmaster UK, another additive was used to produce not just fibres, but complete non-woven textile samples. Figure 9 below indicates the results from the comparative work that was presented at Novatec in 2010.

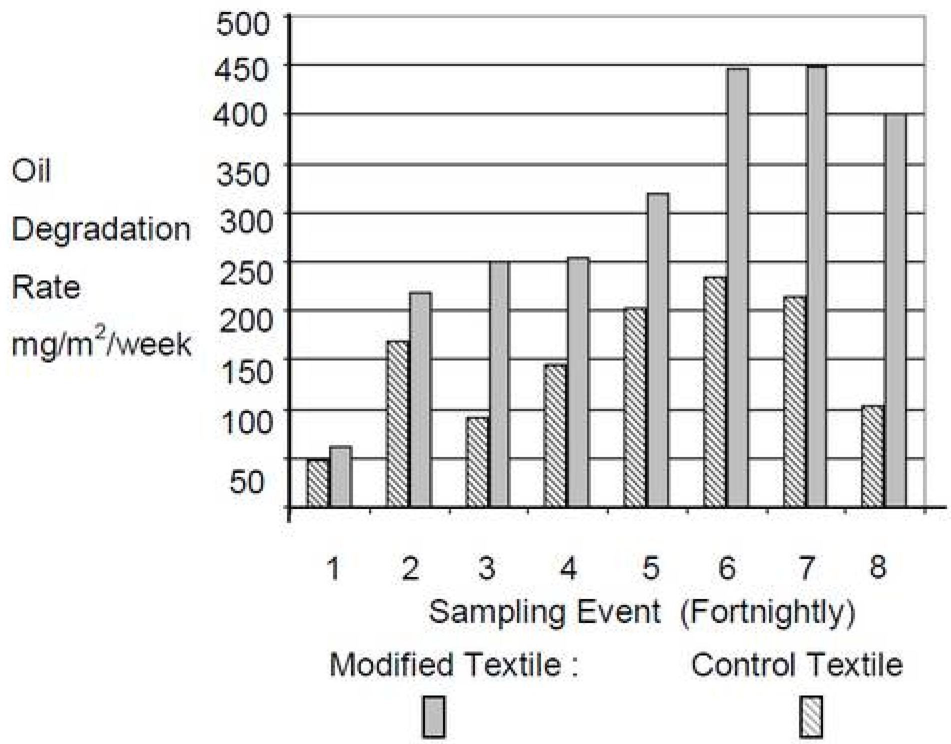

Figure 9: *Comparison of Mean Oil Degradation Rates on Modified and Control Geotextiles (n=3) (Newman et al., 2011a).Copyright IWA Publishing, reproduced with permission.*

One could be critical of this paper in that it represents only a very early snapshot of the data (16 weeks into the experiment). Clearly, one cannot really predict from this data the long term performance of the enhancement in biodegradation rates. This is, however, an ongoing process and the continuing work is discussed in chapter 6. It must be admitted that the mechanism used to change the air within the test rigs was probably less than 100% efficient and thus calculation of oil degradation rates from the measured carbon dioxide concentration is probably subject to some error. Subsequent publications have presented the data as simple comparisons of the measured carbon dioxide concentrations, a situation that is, in hindsight, more valid.

CHAPTER 6

DISCUSSION, CONCLUSIONS AND FURTHER RESEARCH

The purpose of this chapter is to cover the areas of discussion which have not been covered elsewhere in the text. This chapter also covers the overall conclusions arising from the programme of work and indicates the continuing nature of the programme and opportunities for further research. It is thus divided into four sections, a critical discussion of the overall programme, some concluding observations which then leads onto a discussion of ongoing and further work before concluding with some final personal comments.

6.1 Critical Discussion of the Programme

6.1.1 *Background*

The first task of this chapter is to address how the work reported in the portfolio could have been improved and to highlight, with the benefit of hindsight, the criticisms of the Outputs that are not dealt with elsewhere within the document. Obviously there are numerous improvements which could have been made (or negative aspects of the works which could have been avoided) if there had been unlimited, or at least highly enhanced, resources and if the candidate had been fortunate enough to have an entirely free hand. However, in reality, both resource limitations and constraints imposed by the requirements of the industrial collaborators and other funding sources have had a major influence on both the direction and execution of the research. A good example of this is the requirement by the Landfill Tax Credit Scheme funders (WREN) to delete some important fundamental aspects from an otherwise successful proposal to leave room for more applied work on using recycled aggregates.

This is not to say that the candidate feels that the commercial influence over the works reported is an exclusively negative issue. To the contrary, the focus provided by the needs of the industrial partners has been a significant contributory factor in the success of the whole programme and has certainly been an important part of the learning opportunity that this programme of research has provided the candidate. The opportunity of combining academic research with near-market development and to observe the interplay between the two has been invaluable. However, to achieve significant improvements to the work carried out under the same prevailing circumstances could have been more difficult than might appear to be the case but, clearly, not all of the criticisms are related to these constraints and in retrospect there are things which could and should have been done differently.

6.1.2 *Criticisms Addressed Elsewhere*

Another factor for the reader to consider is that the portfolio presents only a number of milestones in the research carried out in the 15 years or so that is covered by the portfolio. In particular, the candidate freely acknowledges that Outputs 1 and 2 do not represent complete closure of the studies included and indeed both might be considered to be preliminary pieces of work. The inclusion of Output 3, a retrospective review of several years of the Coventry University PPS research group's work, was intended to go some way to illustrate that the work had continued to more complete stages, in most cases with the direct involvement of the candidate but, in some situations, with the candidate taking more of an overview role. Where further progress has been made, beyond the work included in the portfolio, the candidate has endeavoured to ensure that the publications have been referenced and that their significance has been highlighted. Thus at least some of the criticisms which might arise from reading this critical overview and accessing the constituent portfolio Outputs were subsequently addressed by the candidate in works published during the time frame of the portfolio but not selected for inclusion. In other cases the required research questions raised were subsequently answered by students under the candidate's supervision which took the work further and the results are available within those students' PhD theses (Bond, 1999; Coupe 2004; Nnadi, 2009; Puehmeier, 2009; Spicer, 2006).

6.1.3 *Living with Early Decisions*

A criticism that could be made in relation to the earlier phase of the research programme was that a significant amount of effort was put into earlier studies on the PPS using a particular type of paving block, the CeePy® block. This was invented by Professor Chris Pratt and had large infiltration cores compared to commercial designs which were developed later. At the time the research programme started they were available commercially from Formpave Ltd (which had licensed the design of the pavement from Coventry University). Having established a series of experiments using the large stock of blocks which were held in the University, the fact that these blocks were going out of production was not taken into account for some years and thus the work was undertaken using obsolete blocks. This includes the work reported in Outputs 1 and 2 and the majority of work reported in Output 3. This throws doubt on the validity of the results in relation to pavements paved with other types of block. The oxygen and water relations of the system would be expected to be different to that for other blocks. It was not until a new supply of the CeePy® blocks were requested from the manufacturer in 2000 that their commercial demise was identified. The demise resulted from developers not liking the shopping trolley-unfriendly surface of the installed blocks and the impracticality of walking on it in heels. To start the experiment again, using models which utilised more appropriate blocks, might have been the correct response, but a decision was made to persist with the ongoing experiments using the well established test rigs in an attempt to maintain data continuity. In retrospect this could be considered a mistake. However, in later experiments the paving blocks used were either Formpave Aquaflow (market leaders in blocks at the time) or, in the case of the research on the Permaceptor® and on the outdoor experiment included as part of Output 4, very similar competitors blocks, which were at that time being used by the companies funding the research.

6.1.4 *Some Blind Alleys in the Research Programme*

An important example of a line of research which became something of an avoidable blind alley is the early work on nutrient enriched geotextiles. This was originally published as Spicer *et al.,* (2006) and was reviewed in some detail as part of Output 6. The work carried out illustrated that the principal of using the fabric of the geotextile as a carrier of the slow release fertilizer was sound but in practice this was as far as it went. Whilst the chosen additive proved to be a technological and scientific success, it was not found practical to develop it into a product because of the cost and availability of the starting materials. A financial evaluation of the potential product before, rather than after, the research phase would have directed the candidate to base the research on the cheaper inorganic additive, which formed the basis of the practical work reported in Output 5.

Whilst disappointing at the time (particularly to the industrial collaborators in the EPSRC CASE award) this was a lesson well learned and certainly one which generated further research opportunities which were readily embraced.

There are also a number of other “blind alleys” which, in retrospect, may have been better either not followed or followed to a more appropriate conclusion.

One of the best examples of this is the great efforts which were carried out to study the PPS microbial communities by molecular methods (Newman *et al.,* 2001; 2002b; 2002c; 2006a) The aim had initially been to develop a numerical measure of microbial diversity as a means of following, quantitatively, the development of the biofilm. After finding that the information could only be partially obtained using standard ITS primers (see Newman *et al.,* 2001) there was an extensive period of method development using DGGE primers before the molecular data in Output 3 could start to be generated. In retrospect it should also have been clear, quite early, that the resource implications of using molecular methods would have made the approach less attractive than the potential alternatives. This being said some very important information did arise from this work and the deposit of the sequences derived from the PPS models in the databases used by HRI may provide important fundamental information to researchers who have the funds available to progress the fundamental aspects of this work.

6.1.5 *Analysis and Sampling*

Criticism should also be raised in relation to the analytical methods used for the determination of oil in almost all stages of the programme. Solvent extraction/ infra-red methods (ASTM, 1990; 2004) were adopted at an early stage. Whilst data continuity might be cited as a reason for continuing the method rather than changing to a chromatographic method, in all honesty, a degree of inertia and a desire for incoming researchers to apply their time to studying pervious pavements, rather than working up new analytical methods, was probably a more realistic reason. Some work was carried out, perhaps late in the day, to compare the IR results with those of an accredited laboratory (STL-Torrington Avenue, Coventry) using a chromatographic method for samples without a free phase. Compared to the chromatographic method, the IR method appeared to have a high bias, typically reporting about twice the chromatographic result. Since this represents a fail-safe situation in evaluations of the effectiveness of the PP system, this was considered acceptable but in hindsight it may have been better to have adopted a chromatographic method from the start, at least for those samples which were expected to have relatively low oil concentrations. The limit of detection of the IR method varied with volume extracted but was typically 0.1 - 0.5 mg/l.

On the other hand, with some of the very high loading experiments the sampling error associated with the presence of significant amounts of free product may have made such efforts redundant. If a PP system is overloaded to the extent that a continuous, macroscopic, layer of free product is in the sample bottle, the absolute values obtained might be considered immaterial.

Obtaining a representative sample from an effluent stream which potentially contains two phases and where one phase appeared in the effluent intermittently, was always going to be difficult. As indicated above, where the free phase dominated the sample, the difference between one catastrophic pollution event and another would be of little consequence but where the free phase was represented by an intermittent thin sheen (or the occasional droplet), sampling became more significant. It had been expected that the experiment resulting in Figure 4 in this document, would produce free phase-containing samples. The development of a sample splitting device which would, without the use of electrical power, be able to split the effluent stream, rejecting the majority but generating composite samples which did not overfill the container between sample collection events had been started. It was intended that the samples so obtained would be representative of the effluent, and weighted so as to give a flow weighted sample. Figure 10, which is a composite image derived from Puehmeier *et al.,* (2004b), illustrates the "tipping bucket" device which would have been used had the destruction of the test car parks in Coventry not been carried out at such short notice.

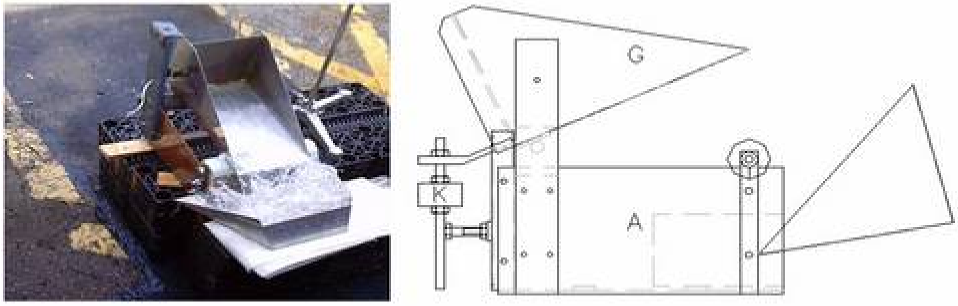

Figure 10 : *Tipping Bucket Sampling Device (adapted from Puehmeier et al ., 2004b) Copyright GRAIE reproduced with permission.*

This device, although perfected too late, proved very successful, with the mean of applied and measured oil concentrations being 1.4 and 1.5 g/l respectively for 6 ten-tip sampling events.

6.1.6 *Operation of the Experimental Rigs*

Another criticism related to the sampling and analysis programme was the effort put into the regular measurement of oxygen and carbon dioxide concentrations within the experimental systems. The automated analyser, which used 15 minute cycle time around 5 ports within the system, produced a plethora of detail which was largely lost by the averaging process which was applied to allow the data to be presented in a reasonable manner. In retrospect, the much simpler approach adopted in later experiments, sealing the system and taking an integrated sample above the headspace, was found to be more than adequate. At the time that the outdoor rigs were being built the candidate had considered using an integration system using sampling bags, rather than an automated, recording system and, in retrospect, this may have proved more useful, if suitable sampling bags could have been obtained. It would have been possible to measure much smaller differences in carbon dioxide concentrations during the initial establishment of the oil degrading communities if the samples could have been applied to the, much more sensitive, off-line analyser, available within the department if simple grab samples had been used, rather than persisting with the less sensitive automated system. In relation to Output 6 it must also be admitted that the mechanism used to change the air within the test rigs was probably less than 100% efficient and thus calculation of oil degradation rates from the measured carbon dioxide concentration is probably subject to more error than might be expected. Subsequent publications have presented the data as simple comparisons of the measured carbon dioxide concentrations, a situation that is, in hindsight, more valid.

An important criticism of the experimental designs used in this work is that nothing has ever been done to replicate the alternate loading and unloading that occurs in trafficked areas. The mechanical attrition which would ensue may have had an important influence in biofilm formation or on the change in nutrient recycling rates which would ensue from the mechanical breakdown of microbial cells. Far more importantly, those geotextiles which incorporated slow release fertiliser additives could show very different release rates if the textiles were subjected to regular frictional abrasion. This is certainly part of the release mechanism for biocides released from plastic floor tiles (Paul Morris, AddMaster UK Ltd, Pers. Com. 2010).

6.2 Concluding Observations

6.2.1 *Re-addressing the Objectives of the Programme*

Associated with the aims expressed in Chapter 1 were a number of objectives a-d. They consisted of two which were largely related to oil biodegradation within the PPS and two more closely related to oil retention in both standard and modified systems. It is appropriate here to readdress these and consider the extent to which they were reached.

6.2.2 *Objectives Related To Oil Biodegradation*

The research represented by Outputs 1-3 are examples of research that had been undertaken to address objectives a and b and, as a consequence, increase the fundamental understanding of processes taking place within the PPS, thus addressing the first aim of this programme.

The first of the objectives was:

Determine whether PPS are capable of maintaining complex, self sustaining, oil degrading, communities of microorganisms over extended periods and to identify the external inputs required to achieve this.

Outputs 1-3 have served to illustrate the capabilities of the PPS to retain and degrade hydrocarbon, which in turn has served to increase the take-up of pervious pavements (there was a steady increase in the use of pervious pavement blocks between the start of the project and 2005 when Output 3 was published). The results have also provided an incentive for commercial organisations to fund further research (the research income generated during this research programme is ample evidence).

Outputs 2 and 3 both address the external inputs of the microorganisms required to create an oil degrading ecosystem. This was addressed in relation to eukaryotes in Output 2 and in relation to prokaryotes as a part of Output 3 and also as part of Output 5 (in Puehmeier, *et al* 2005). It is now recognised that commercially available microbial seeds are not necessary for the long term establishment of oil biodegradation in a PPS. However, even as late as 2007, when the candidate established the test rigs used in Output 6, the use of an inoculum from a pre-existing oil degrading experimental rig was used to reduce the lag period. In a real car park , with an appropriately designed system, the retention of oil would be sufficiently good not to require oil biodegradation, either during the start up period or in the winter months when low temperatures limit the degradation rates (Brownstein, 1999). Output 2 was also able to demonstrate the rapid recovery of the system after periods of water and nutrient depravation. However, the most important input to the PPS was found to be inorganic nutrients, in particular Phosphorous.

The second biodegradation-related objective was:

Develop a means by which required inorganic nutrients could be made available to the oil degrading microorganisms in a PP in a highly effective way whilst minimising losses of inorganic nutrients to ground or surface waters.

Outputs 1, 2 and 3 demonstrated that long term provision of inorganic nutrients produced greatly enhanced biodegradation but it was only the train of research effort, exemplified by Output 6, that presented the opportunity to achieve this in a manner that delivered the inorganic nutrients over the very long term and at the position where they are of greatest use to the microorganisms. Clearly much work remains to be done in this area but the principles appear to be well established.

Output 6 exemplifies one stream of this effort. It presents an opportunity for the geotextile, the site where the majority of the oil is trapped within these PPS designs, to become a source of inorganic nutrients to encourage oil biodegradation. In the long term it is hoped that they will be incorporated into the enhanced oil retaining geotextile presented in the 2006 patent (Newman *et al*., 2006b). This in turn would be capable of playing an important role in the treatment train of both normal PPS applications and the MPPS allowing the prospect of the PPS reaching the peak of its development.

Outputs 1-3 (and the related lines of research that were informed by them) which are discussed in Chapter 2 of this document resulted in a number of key conclusions. The first was the importance in a PPS based bioreactor of the inorganic nutrient delivery mechanism. The second was the importance of eukaryotic organisms to both the regulation of the system and as a means of assessing microbial biodiversity. Finally, there was the recognition that commercially available oil degrading mixture of organisms was, in time, replaced by a communities which was, presumably, better adapted to the PPS environment and that, in the absence of the inoculum, oil degrading activity could be established with limited delay. Thus, it can be said that objectives a and b, which largely addressed the biodegradation of oil in the system, were essentially achieved in most cases but that work remains to be done.

6.2.3 *Objectives Related to Oil Retention*

The second aim of this programme led to the establishment of objectives c and d, which were largely associated with long term oil retention rather than biodegradation of the retained oil. These aspects are particularly important because the kinetics of oil biodegradation in PPS, and the largely random nature of distribution of oil deposits, are such that the system requires time to establish the oil degrading assemblage and to hold onto the oil strongly enough that significant degradation can be achieved. There are limits to this and thus objective c. was established:

> *Study the response of traditional PPS to catastrophic vehicle oil losses and explore a practical system to allow the use of the PPS in highly sensitive environments or high oil spill-risk areas.*

This objective starts with the recognition that the oil retaining capability of a standard PPS would be overcome in a realistic oil-loss scenario, as illustrated in Newman *et al.* (2004a), which forms a component part of Output 4. This paper was essentially the means by which the first part of the above Objective was successfully addressed, particularly through the experiments which produced Table 1, and Figure 5. The work included in this paper led to an acceptance that, whilst a significant oil loss event would result in the retention of a large **proportion** of the oil, there would be an ongoing and unacceptable loss of hydrocarbons to controlled water and this provided a clear justification for the next stage of the work.

The candidate’s response to this finding was the invention of a device which allowed gravity separation of free phase hydrocarbons to take place in the low energy hydrological environment of an extensive PPS subbase i.e. the patent included in Output 4. Validation experiments indicated that the system offered a tremendous improvement over the original Pratt design but the system has only achieved commercial success in niche applications. Whilst achieving commercial success was not one of the objectives, this situation was disappointing because a regular input of licence payments could have produced a good funding stream to allow some of the less commercial aspects to be researched. We must also remember, however, that the gravity separation principle is an essential operating principle of both the OSCD and the FMD, which form the active components of the MPPS presented in Output 5.

Thus the experience gained in developing the invention which constitutes Output 4 significantly informed the steps required for the development of both component devices which constitute Output 5. This intimately linked pair of inventions has lead to the availability of a practical, environmentally sound, macro-pervious pavement, which is a significant contribution to the availability of a SuDS approach to draining hard paved surfaces when the adoption of pervious surfaces is resisted i.e. addressing the final objective:

> *Establish a practical approach to the use of pervious subbases in the absence of a pervious surfaces where developer resistance is leaning towards positive drainage because of mistrust of the pervious surfaces available*

6.3 Ongoing and Future Work

6.3.1 *Continuing Work on the MPPS*

One of the largest examples of the hybrid-subbase form of the MPPS has been installed in the form of a large car park. In response to the concerns of the regulator, monitoring points were included in the installation of the car park downstream of the MPPS elements. This installation is currently the subject of a long term on-going research effort by the candidate involving the monitoring of the outflow points and measurement of the amounts of sediment and oil trapped in the OSCD network. The results to date are proving to be an excellent endorsement of the design. In addition to this currently ongoing work, there are well developed plans for further work on the floating mat system, both in terms of incorporating the developments in geotextiles exemplified by Output 6 and also with work relating to the optimal positioning of the floating mat equipped boxes at the outlet of either an attenuating PPS or a MPPS, to act as a final polish prior to release.

6.3.2 *Continuing Work on Geotextiles*

Work on the self fertilising geotextile is also ongoing and is likely to be so for some time. The paper presented in the portfolio is not the latest publication. It has been updated in a more recent conference paper. Whilst it is not possible to present the full paper it is worthwhile here to include a figure used during the oral presentation at a conference in 2011 (Figure 11) (more current than the published version of the paper in the proceedings (Newman *et al.,* 2011b)).

It can be seen that the microbiological system on the modified geotextile continues to respond to additions of oil, giving a clear advantage over the untreated textile. As the biofilm in the untreated textile system becomes better established, through inputs of nutrients from outside (particularly P inputs from the oil (Barnes *et al*., 2001)), it is expected that the differences may reduce with time. How long this will be remains to be seen but at the time of writing, some two years into the experiment, the advantage is still present. Further work to incorporate both nutrient release and enhanced oil retention is a research line which demands attention but this will, necessarily, require considerable input from commercial partners whose assistance in producing the modified textiles will be essential.

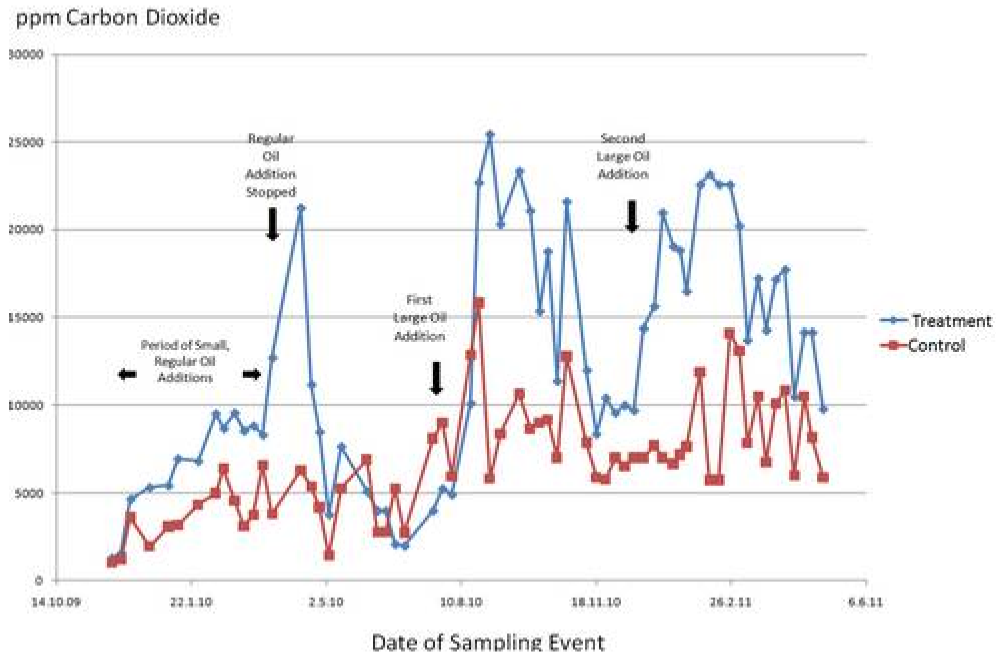

Figure 11: *Comparison of oil degrading performance of modified and control geotextiles. Figures shown are mean values (n=3). Originally presented at* oral presentation associated with Newman *et al.,* 2011

6.3.3 *The Relative Costs of PPS and Other Systems*

An issue that has not yet been considered in this overview is the cost of various PPS systems relative to each other and to other SUDS and non-SUDS alternatives. A detailed costing exercise has not formed part of the portfolio and has not formed one of aims of the candidate. However, below is an opinion based upon information gleaned from discussions with industrial collaborators over the many years in which this work has progressed.

There is no doubt that pervious block pavers are more expensive than standard block pavers (as much as double) but with the advent of growing competition this differential is likely to fall. However to compare the cost of a PP with a standard pavement, without realising that it is also part of the drainage system, and thus taking into account the costs of pipework etc. which it is replacing, is to miss the point. There are also issues such as a need not create falls on the surface when laying the PP which can also provide cost benefits.

Generally speaking when all other costs are taken into account the cost differences are not so great as to be prohibitive as indicated by the fact that the proportion of pervious to impervious pavements continues to increase, albeit from a small base (Frazer, 2005).

Each installation will, inevitably, have a different cost implication but one must look at this in the context that a developer would only be contemplating a SUDS drainage system if it had been imposed on him by a regulatory decision or he had some other overriding reason to take a SUDS approach (e.g. to create a better environmental image for the project). Thus it is also important to compare PPS with other SUDS installations.

The most relevant of these relate to provision of additional storage in ponds swales or wetlands and it is over these that the PPS offers the greatest benefits in that it represents zero loss of land for the developer. Where infiltration is possible soakaways and dry wells might be a cheaper option but, where infiltration is not possible and the aim is attenuation, the use of oversize pipes or hard sub-surface reservoirs are the only alternatives if land take is to be minimised. Here the costs would be greater than that for PPS. If one now looks at the relative cost of PPS with stone subbase/storage elements and PPS with a plastic box subbase replacement it is clear that the plastic box system is more expensive but one must also take into account that the void ratio is higher and thus the boxes are installed to shallower depth. There is less excavation and less soil to be disposed of with the plastic box. Furthermore, if the soil is contaminated the disposal costs will start to multiply rapidly and thus on specific projects the plastic box can become very competitive. Importantly, the shallow depth of the box system allows the height at which water is stored and transmitted to be kept higher than any existing drain to which the system is connected. This avoids relaying of-site drains and the need for pumping devices.

Finally we might consider the relative cost of the MPPS when compared to the standard PPS. The system allows the developer to use cheaper asphalt surfacing rather than block paving or porous asphalt but the channel drains have a cost that would need to be taken into account. Again careful costing on each specific project is the key to achieving the best solution.

This argument has so far looked only at the internalised costs. The cost of providing additional sewerage capacity and extensions to treatment works are not considered by developers but should be considered by planners and other regulators, as should the costs of flooding which seem to be highlighted on our TV screens with great regularity. The problem with economic assessments of technology is that they quickly become dated. An up to date and rigorous economic assessment, taking into account both internal and external costs of PPS, is certainly an area of research which would be very useful.

6.4 Final Remarks

Finally, the candidate would wish to make a comment on what he feels have been the two most important things he has learned from the work reported here. This work has involved interaction with numerous scientists, engineers, industrialists, regulators, developers, politicians and the general public. The first is that within this field there are so many disciplines which can be brought to bear that it is impossible to make real progress without taking an interdisciplinary approach and being prepared to involve an ever changing spectrum of collaborators, integrating the various contributions of disciplines ranging from civil engineering to synthetic chemistry.

However, even more important is the realisation that the science and engineering is only the first stage in the process. Equally important is the changing of hearts and minds amongst regulators, engineers and developers, as well as the general public. With the potential effects of climate change likely to put ever increasing loads on urban drainage systems the ability of scientists to persuade others that doing something with drainage that is outside their comfort zone or spending a little more now to prevent environmental consequences later is the important next step. If we believe the science works we need to communicate it.

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Appendix 1- Numbered List of Outputs

Output 1

C.J. Pratt, A.P. Newman and P.C. Bond (1999), Mineral Oil Bio-Degradation Within a Permeable Pavement: Long-Term Observations., *Water Science and Technology*, 29, (2), pp. 103-109.

Output 2

A.P. Newman, C.J. Pratt and S. Coupe (2002), Mineral Oil Bio-Degradation Within a Permeable Pavement: Microbiological Mechanisms., *Water Science and Technology*, 45, (7), pp. 51-56.

Output 3

A.P. Newman, S.J. Coupe, H.G. Smith, T. Puehmeier and P. Bond (2006) The Microbiology of Permeable Pavements., Proceedings 8th International Conference on Concrete Block Paving, November 6-8, 2006 San Francisco, California, USA, pp.181-191.

Output 4

Permaceptor® PPS System - Illustrated by:

i) European Patent Specification EP 1 446 536 B1, A. P. Newman, *Pollutant Containment System*, International Publication Number WO 2003/040483, Date of Filling 11/11/2002

ii) S. Wilson, A.P. Newman, T. Puehmeier and A. Shuttleworth (2003), Performance Of An Oil Interceptor Incorporated Into A Pervious Pavement, *Institution of Civil Engineers Proceedings: Engineering Sustainability*, 156,(ES1), pp. 51-58.

iii) A.P. Newman, T. Puehmeier, V. Kwok, M. Lam, , S.J. Coupe, A. Shuttleworth, and C.J. Pratt, (2004), Protecting groundwater with oil-retaining pervious pavements: Historical perspectives, limitations and recent developments, *Quarterly Journal of Engineering Geology and Hydrogeology*, 37, (4), pp. 283-2 91

Output 5

Practical Macro-Pervious Pavement System - Illustrated by:

i) UK Patent GB 2 399 567 A, Inventor: A.P. Newman, (Date of filing Oct 2004) Liquid Storage Module Containing a Buoyant Component.

ii) European Patent EP1 53 428 A2 : Inventors: A. Shuttleworth, A. P. Newman, and T. Puehmeier, *Drainage Element*, ,(Date of European publication 25/5/2005) UK Patent GB2409872 (Date of GB Filing 19/11/2003) Grant of Patent 14/7/2010

iii) T. Puehmeier, D. De Dreu , J.A.W. Morgan , A. Shuttleworth and A.P. Newman (2005), Enhancement of Oil Retention and Biodegradation in Stormwater Infiltration Systems, In: *Proceedings of* *the 10th International Conference on Urban Drainage*, Copenhagen, DEN, 21st-26th August 2005. International Water Association, London, UK, CD-ROM

Output 6

A.P. Newman , E.O. Nnadi, , L.J. Duckers and A.J. Cobley (2011) Further Developments in Self-Fertilising Geotextiles for Use in Pervious Pavements., *Water Science & Technology*, 64, (6), pp.1333-1339

Appendix 2- Contribution of Other People to the Outputs and Research

Having been carried out over a period of over 15 years the work presented in this portfolio has been contributed to by a large number of different collaborators.

- The candidate was the lead researcher and apart from Output 1 proposed the original ideas for the research and undertook development of the various experimental designs. The candidate was the sole originator of two of the patented devices presented in this portfolio and was a significant contributor, along with Tim Puehmeier and Andy Shuttleworth, to the other patent. The candidate brought to this programme skills in analytical sciences and environmental microbiology as well as the experience in pervious pavement research developed prior to the start of this portfolio.
- Professor Chris Pratt was important in establishing the work since the original design from which this work developed was his but from around 1998 onwards his input became less important as the project moved into areas of biology beyond his expertise. However, as Head of Civil Engineering and later Dean of the School of Natural and Environmental Sciences he played an important role in obtaining internal funding during the early part of the programme. From 2004 onwards his input was largely in terms of internal reviewer and member of the KTP management committee. At this time important inputs from industrial partners in the KTP schemes began to become more dominant.
- Paul Bond was a research student at the time that Output 1 was published and at the time of Output 1 had been largely following a range of experiments previously established by the candidate during his supervision of a previous student (Jon Brownstein).
- The most regular collaborators in this programme of research were Tim Puehmeier and Steve Coupe. Tim was TCS/KTP associate for part of the period of collaboration, Steve Coupe was supported on a grant obtained by the applicant from the Landfill Tax Credit Scheme and on a KTP scheme (where the candidate was lead academic) in collaboration with Formpave Ltd . They had both also been internally funded for research carried out early in the research programme. Steve Coupe largely brought his expertise as a protozoologist and was, from time to time, assisted by Humphrey Smith, largely on identification of Protozoa, in a proportion of the work reported in Output 3. Initially Tim Puehmeier was largely contributing his molecular biology skills. However, through the KTP process Tim's contributions rapidly moved sideways and he was very closely involved with the experiments to validate the Permafilter Geotextile. He was also largely responsible for all the negotiations with technical textile manufacturers to bring the Permafilter Geotextile into prototype production, an important step which was a necessary pre-requisite to the work reported in Output 6.
- The industrial collaborators important to this portfolio were Andy Shuttleworth and Steve Wilson who both worked for companies closely linked to the Dutch company, Permavoid Ltd. Permavoid was the assignee in all but one of the patent applications included in this portfolio (as per the IP agreement between CU and SEL

Environmental, the industrial partner in the KTP programme involving Tim Puehmeier).

The following paragraphs indicate the contributions made by others to the funding, design, management, execution and writing of the components included in the various outputs certain people who made shorter term but equally important contributions to the programme.

Output 1 - Was funded by a University PhD studentship with funds derived from the licence income from Formpave's use of the IPR held by the University on the PPS. The day to day work was carried out by Paul Bond under the direct supervision of the Candidate. The experiment was managed by the candidate and the experimental design arose from discussions between the three authors. The test rigs etc were largely derived from rigs built under the candidate's supervision by Jon Brownstein the previous PhD Student. The paper was originally written by Professor Chris Pratt with the candidate and Paul Bond both making significant contributions after the first draft. The oil application regime adopted was based on a combination of literature data and data obtained in work reported as Newman *et al*.,(1998) which was largely carried out under the supervision of the candidate by a visiting German exchange student, Jörn Krogmann.

Output 2 - Was also largely funded by an internal studentship. Some additional funding came from a grant obtained from the (now defunct) Category 3 Landfill Tax Credit Scheme with the funds provided by Waste Recycling Environmental Limited and the Environmental Protection Group Limited. The day to day work was carried out by Steve Coupe under the supervision and management of the candidate. Because Coventry University had just dismantled its electron microscopy suite the electron microscopy was carried out at the Manchester Metropolitan University (MMU) using samples derived from novel electron microscope stubs. These were designed by the candidate and constructed in the mechanical workshops in the James Starley building. This work was done jointly by the candidate and Neil Cresswell along with MMU technical staff. Figures 5 and 6 represent extensions of work previously reported in Output 1. The medium rigs used in this project were to a design previously put forward by Jon Brownstein but the small rigs were to the candidates design and constructed in the James Starley Building workshops. The paper was written by the candidate but with significant inputs from Chris Pratt and Steve Coupe.

Output 3 – This is a paper which reviewed the Coventry PPS research groups outputs in the field of the microbiology of porous pavements. The paper was almost entirely written by the candidate but with significant input, including the abstract, from Steve Coupe. The authors listed are the principal co-authors from whose sections of papers were extracted. The paper was presented at a Conference in San Francisco which was attended by the candidate using funds pledged initially by Formpave Ltd. but actually provided by Hanson–Formpave after their takeover of the company. Figures 1, 3, 4 and 5 were produced from the same programme of work as Output 1. Figure 2 was based on an original idea by the candidate for a novel multiple tube method for determining oil degrading microorganism concentrations and using samples derived from a Permaceptor test rig (see Output 4). Figure 7 was previously published in Output 2. Figure 6 is extracted from Newman *et al*., (2002b). This work was based on an original grant application for a quantitative measure of PPS microbial health originally made by the candidate (to WREN). However it was carried out by Tim Puehmeier as part of a KTP Scheme funded by EPSRC and SEL Environmental (a division of Site Electrical Ltd, Bury) but was actually done at HRI in Wellesbourne under the day to day supervision of Alun Morgan and the overall management of the candidate. The Work reported in figure 8 was carried out by Steve Coupe with assistance, in protozoan ID, provided by Humphrey Smith. The candidate was responsible for experimental design. The work was managed by the candidate as part of the Landfill Tax Credit Scheme funded project mentioned above.

Output 4 – This Output is actually an invention which is principally represented by the European version of the patent but this document is supported by a journal paper which contains details of parts of the validation process. This was based on an original idea by the candidate and the candidate is listed as the sole inventor.

- The patent was written by a patent agent under the direction of the candidate. Funding of patenting was provided by Coventry University Enterprises but the IPR was licensed to SEL Environmental for a period of 5 years. SEL Environmental funded much of the validation work.

- Steve Wilson designed the test rig used to validate the Permaceptor (as described in Wilson *et al.,* (2003). The building of the rig was supervised by Andy Shuttleworth. The experimental design was a joint effort between Steve Wilson, Tim Puehmeier and the candidate and the work was carried out jointly between them. Some analysis was done on a commercial basis by Severn Trent Laboratories.

- The other paper included as a part of Output 4 (Newman *et al*. 2004a) was partly a review of previous work but included significant amounts of new work related to the Permaceptor. The contributions of, Stephen Coupe, Andy Shuttleworth and Chris Pratt have already been identified. The paper was written solely by the candidate. Manfred Lam was responsible for the work which generated Figure 4 and Vicki Kwok was responsible for the work which is illustrated by Figure 7 and reported in Table 1. Both these undergraduate project students carried out this work under the candidate's direct supervision using test rigs designed and built by the candidate who also largely undertook the experimental design. The experiment which gave rise to figure 5 was carried out jointly by the candidate and Tim Puehmeier. Figure 6 is a diagram originally produced by the candidate as part of the patenting process.

Output 5 – Is another invention or, rather, 2 intimately linked inventions which have a rather complex provenance. The Output is represented by 2 patents and a conference paper.

- The first patent, the FMD, is one which was based on a novel idea by the candidate and the candidate is listed as the sole inventor. The patent itself was written by a patent agent based on detailed information provided by the candidate and diagrams contained within other patents held by the applicant (Permavoid Ltd). The invention depends significantly on a, previously patented, load bearing subbase replacement unit. After the patent application the development and validation experiments were carried out largely as a joint effort between Tim Puehmeier and the candidate. The development was funded by of a KTP Scheme funded by EPSRC and SEL Environmental ,at that time a division of Site Electrical (PH) Ltd , Bury.

- The second patent, the modified channel drain, is a joint invention between Andrew Shuttleworth, Tim Puehmeier and the candidate.The patent was written by a patent agent under the supervision of Andy Shuttleworth. Following the patent application various commercially produced versions of the product were subject to validation tests carried out jointly between Tim Puehmeier and the candidate. The key modification (post patent application) was the design of the cover between individual units. This was based on an original idea by the candidate. The post-patent application development work was funded by the above KTP scheme.

- The conference paper, Puehmeier *et al.,* (2005), includes three aspects of the work on the two patented devices. The paper was written entirely by the candidate. The design for the floating mat cross section, the novel model chambers used for the long term experiments and the test bed used for the channel drain was the candidates work. Lee Warwick at SEL constructed the test bed under the supervision of Andy Shuttleworth. The experimental design for the channel drain experiment was the candidate's and carried out jointly between the candidate and Tim Puehmeier. Some analytical work was carried out on a commercial basis by Severn Trent Laboratories. The electron microscopy was carried out at MMU by the candidate with the assistance of the MMU technical staff. Dies De Dreu, a Dutch exchange student, was responsible for the routine carbon dioxide monitoring in the long term experiments. Alun Morgan, of HRI Warwick, provided guidance and resources for the DGGE work reported in this paper (and in other papers not submitted as part of the portfolio but important in providing the fundamental understanding upon which the portfolio is based).The DGGE work was carried out by Tim Puehmeier using materials generated in a long term experiment carried out by the candidate.

Output 6 - This journal paper is based on experiments designed and almost exclusively carried out by the candidate with the following exceptions.

- Ernest Nnadi carried out some of the phosphorus determinations and did occasional carbon dioxide measurements when the candidate was unavailable.

- The research was carried out with financial and in-kind support from EPG Ltd and Permavoid Ltd.

- The modified textile was provided by AddMaster UK Ltd.

- Since, after a 7 year gap, Coventry University again had an SEM, the work was done in house. Andy Cobley operated the coating device used for the SEM work and Les Duckers produced the SEM images used. They provided this service for a number of conference presentations in which the SEM images played a major part.

Appendix 3

Selected On-Line Government and Industrial Guidance Documents Which Cite Outputs Used in This Portfolio.

Official and Semi-official Guidance

Toronto and Region Conservation Authority
http://www.creditvalleyca.ca/sustainability/lid/stormwaterguidance/downloads/guidelines-break/b2-CoverPage-Ack-TOC-Preface.pdf
http://www.sustainabletechnologies.ca/Portals/_Rainbow/Documents/PPBS%20Final%202008.pdf

Washington State Dept of Transport
http://www.wsdot.wa.gov/NR/rdonlyres/69E02461-0553-4EAE-9DA5-1F85EC93E74F/0/PavementPreservation.pdf

Low Impact Development Center, Maryland
http://www.lid-stormwater.net/permpavers_benefits.htm

US EPA
http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=137&minmeasure=5

http://water.epa.gov/polwaste/nps/urban/upload/2005_12_08_NPS_urbanmm_urban_ch05.pdf

North Carolina State University
http://www.bae.ncsu.edu/stormwater/PublicationFiles/PermPave2008.pdf

Iowa Dept of Transportation/National Concrete Pavement Technology Center
http://www.ctre.iastate.edu/reports/mix_design_pervious.pdf

City of Beaverton - Oregon
http://www.greengirlpdx.com/EventRelatedResources/Tours/BervertonPerviousConcrete.htm

Oregon Environment Council
http://www.oeconline.org/resources/publications/reportsandstudies/sstreport

National Co-operative Highway Research Programme
http://books.google.co.uk/books?id=8LNOKW4rOBcC&pg=PA72&lpg=PA72&dq=pavement+AP++Newman&source=bl&ots=cg7slshY6D&sig=RomjQ8YMogkOYhYq23_jPn9JzLs&hl=en&sa=X&ei=IYKNT8OABorF8gPhponPCw&ved=0CFsQ6AEwCA#v=onepage&q=pavement%20AP%20%20Newman&f=false

European Commission/SILVIA project report
http://www.trl.co.uk/silvia/Silvia/pdf/Associated_Reports/SILVIA-TRL-008-01-WP3-240703.PDF

Government of South Australia, Adelaide
http://www.lga.sa.gov.au/webdata/resources/files/Institutionalising_Water_Sensitive_Urban_Design_-_Technical_Manual.pdf

http://www.epa.sa.gov.au/xstd_files/Water/Code%20of%20practice/govcop1.pdf

Puget Sound Action/Washington State University
http://www.psp.wa.gov/downloads/LID/LID_manual2005.pdf

Low Impact Development Centre/Southern California Stormwater Monitoring Coalition
http://www.casqa.org/LinkClick.aspx?fileticket=zhEf2cj4Q%2Fw%3D&tabid=218

South East Michigan Council of Governments
http://www.semcog.org/uploadedfiles/Programs_and_Projects/Water/Stormwater/LID/LID_Manual_chapter7.pdf

Industry and Industrial Association Guidance

CIRIA
http://www.ciria.com/suds/pdf/suds_lit_review_04.pdf

Brick Industry Association
http://www.gobrick.com/Portals/25/docs/Technical%20Notes/TN14D.pdf

Permapave Ltd
http://permapave.com.au/technical/downloads/Modelling%20Permapave%20as%20Water%20Sensitive%20Urban%20Design%20System-1.pdf

Australian Iron & Steel Slag Association
http://www.asa-inc.org.au/documents/ASA_Landcare_Report.pdf

http://www.recycledorganics.com/publications/reports/stormwater/stormwaterreport.pdf

Portfolio of Published Outputs

Most of the outputs pre-date the requirement for “Open Access” and many remain copyright. The items are thus presented as links to the candidates PURE profile pages and where possible with a DOI or a link to the publisher’s web site. Materials that are open access on-line also have a link to the on-line available version (which may not be the final published item.

Output 1: Journal Article

C.J. Pratt, A.P. Newman and P.C. Bond (1999), Mineral Oil BioDegradation Within a Permeable Pavement: Long-Term Observations., Water Science and Technology, 29, (2), pp. 103-109.

https://pureportal.coventry.ac.uk/en/publications/mineral-oil-bio-degradation-within-a-permeable-pavement-long-term

10.1016/S0273-1223(99)00013-X

Output 2: Journal Article

A.P. Newman, C.J. Pratt and S. Coupe (2002), Mineral Oil BioDegradation Within a Permeable Pavement: Microbiological Mechanisms., Water Science and Technology, 45, (7), pp. 51-56.

https://pureportal.coventry.ac.uk/en/publications/oil-bio-degradation-in-permeable-pavements-by-microbial-communiti

10.2166/wst.2002.0116

Output 3: Conference Proceedings Paper (Peer Reviewed)

A.P. Newman, S.J. Coupe, H.G. Smith, T. Puehmeier and P. Bond (2006) The Microbiology of Permeable Pavements., Proceedings 8th International Conference on Concrete Block Paving, November 6-8, 2006 San Francisco, California, USA, pp.181-191.

https://pureportal.coventry.ac.uk/en/publications/the-microbiology-of-pervious-pavements

http://www.sept.org/techpapers/1306.pdf

Output 4 :INVENTION

The Permaceptor PPS System - Illustrated by:

i) Patent: European Patent Specification EP 1 446 536 B1, A. P. Newman, Pollutant Containment System, International Publication Number WO 2003/040483, Date of Filling 11/11/2002 https://pureportal.coventry.ac.uk/en/publications/pollutant-containment-system

ii) Journal Article : S. Wilson, A.P. Newman, T. Puehmeier and A. Shuttleworth (2003), Performance Of An Oil Interceptor Incorporated Into A Pervious Pavement, Institution of Civil Engineers Proceedings: Engineering Sustainability, 156,(ES1), pp. 51-58.

https://pureportal.coventry.ac.uk/en/publications/performance-of-an-oil-interceptor-incorporated-into-a-pervious-pa

https://doi.org/10.1680/ensu.2003.156.1.51

iii) Journal Article: A.P. Newman, T. Puehmeier, V. Kwok, M. Lam, , S.J. Coupe, A. Shuttleworth, and C.J. Pratt, (2004), Protecting groundwater with oilretaining pervious pavements: Historical perspectives, limitations and recent developments, Quarterly Journal of Engineering Geology and Hydrogeology, 37, (4), pp. 283-2 91

https://pureportal.coventry.ac.uk/en/publications/protecting-groundwater-with-oil-retaining-pervious-pavements-hist

https://doi.org/10.1144/1470-9236%2F04-011

Output 5: INVENTION

Practical Macro-Pervious Pavement System - Illustrated by:

i) Patent: UK Patent GB 2 399 567 A, Inventor: A.P. Newman, (Date of filing Oct 2004) Liquid Storage Module Containing a Buoyant Component.

https://pureportal.coventry.ac.uk/en/publications/liquid-storage-module-containing-a-buoyant-component

ii) Patent: European Patent EP1 53 428 A2 : Inventors: A. Shuttleworth, A. P. Newman, and T. Puehmeier, Drainage Element, ,(Date of European publication 25/5/2005) UK Patent GB2409872 (Date of GB Filing 19/11/2003) Grant of Patent 14/7/2010

https://pureportal.coventry.ac.uk/en/publications/drainage-element

iii) Conference Proceedings Paper: T. Puehmeier, D. De Dreu , J.A.W. Morgan , A. Shuttleworth and A.P. Newman (2005), Enhancement of Oil Retention and Biodegradation in Stormwater Infiltration Systems, In: Proceedings of 83 the 10th International Conference on Urban Drainage, Copenhagen, DEN, 21st -26th August 2005. International Water Association, London, UK, CD-ROM

Output 6**: Journal Article**

A.P. Newman , E.O. Nnadi, , L.J. Duckers and A.J. Cobley (2011) Further Developments in Self-Fertilising Geotextiles for Use in Pervious Pavements., Water Science & Technology, 64, (6), pp.1333-1339

https://pureportal.coventry.ac.uk/en/publications/further-developments-in-self-fertilising-geotextiles-for-use-in-p

https://doi.org/10.2166/wst.2011.180