

Further developments in self-fertilising geotextiles for use in pervious pavements

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ABSTRACT

Geotextiles incorporating inorganic nutrients (particularly phosphorous) to enhance the growth of oil degrading microorganisms when geotextiles are used in pervious pavement applications have been shown to be effective in the past. However the cost and manufacturing difficulties have been a barrier to their use. A polypropylene random mat geotextile incorporating an alternative polymer additive as a source of phosphorus has been investigated as a potential self-fertilising geotextile. Experiments are reported which investigate nutrient leach rates, biofilm formation and biodegradation activity.

Key words | geotextiles, pervious pavements, hydrocarbons

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INTRODUCTION

The design of pervious pavement system (PPS) with a geotextile installed immediately below the laying course supporting concrete block pavers is probably the most popular type in the UK. The role of the geotextile as a support for microorganisms which can biodegrade hydrocarbon pollutants passing through the PPS is widely reported as is the effectiveness of a geotextile as an oil retaining layer (e.g. Pratt *et al.* 1999). The aim of this paper is firstly to review progress made to date in relation to the role of inorganic nutrients in biodegrading pervious pavements and previous attempts to incorporate phosphate releasing materials directly into the geotextile fibres. Secondly, it is to report some preliminary experiments on a geotextile produced with a novel, inorganic, phosphate releasing additive which has overcome some of the technical difficulties associated with fibre production using the organic additive previously used.

Inorganic nutrients in oil biodegradation

Nutrient requirements

Systems used for the biodegradation of hydrocarbons require an appropriate nutrient status to convert the compounds into useful intermediate substances for metabolism and ultimately, into cellular material. Many types of nutrient are needed for this process. Macronutrients are needed in

relatively large quantities and a shortage of nitrogen, phosphorus or potassium is often the cause of sub-optimal biodegradation rates (Atlas 1981, 1984; Gruiz & Kriston 1995). In many biodegradation situations, either nitrogen (N) or phosphorus (P) (or both) are the limiting factor in generating the biological population capable of breaking down hydrocarbons. A carbon (C) to N ratio of 10:1 and C to P at 100:1 has been suggested for stimulation of crude oil biodegradation in seawater (Atlas & Bartha 1972) and similar ratios are to be expected in freshwater situations. Micronutrients are needed in much smaller doses and, although their absence is less important, their presence in useful quantities has been shown to stimulate higher biodegradation rates in PPSs (Bond 1999; Pratt *et al.* 1999). We should not forget that some bacteria and fungi have requirements for complex growth factors. These factors depend on the eventual development of a complex ecosystem with protozoa and higher organisms synthesising and releasing a range of organic compounds.

The rate of hydrocarbon biodegradation is heavily influenced by the concentration of usable nutrients within the contaminated area. Degradation of hydrocarbons does occur within the natural environment but at a relatively slow rate (Atlas & Bartha 1972). Although the nutrient status of some sub-surface environments may be sufficient to enable the biomass to recycle carbon in an uncontaminated situation, the exhaustion of nutrient reserves may

rapidly occur if an unfavourable ratio of carbon:nutrient occurs, as often seen when oil is spilled and as illustrated by Pratt *et al.* (1996, 1999) in relation to oil trapped in PPS laboratory models. In common with unfertilised PPS installations, many sub-surface water environments have a sub-optimal nutrient status for hydrocarbon degradation, the duration of clean up is often prolonged and the objective is difficult to achieve (Kämpfer *et al.* 1991). Despite this, the bioremediation of hydrocarbons has been widely reported, including successful remediation of 1,000 gallons of diesel fuel reported by Frankenberger *et al.* (1989). In this study, rupture of an underground storage tank resulting in a maximum concentration of 1,500 mg of diesel per kg of soil. Following injection of a 250 mg per litre nitrate/phosphate mixture with a nitrate phosphate ratio of 10:2 into seven wells dug into the contaminated plume, a 6-month period of biological activity resulted in no detection of hydrocarbons above the limit of detection (<1 mg/kg).

This reflected other research in biodegradation where several studies have found that the addition of N and P to water increases the bacterial decomposition of hydrocarbons. Fertilisation with N and P has been found to be particularly important in situations where the lack of nutrients and high carbon content of the oil limits the rate of biodegradation (Atlas & Bartha 1972; Bragg *et al.* 1994; Swannell *et al.* 1996) and as described below this is reflected in studies applied to PPS.

The porous pavement research group at Coventry University has been involved in the study of oil retention and oil degradation since 1995. The first research reported in this area was by Pratt *et al.* (1995) and Brownstein (1998) who used various indoor models (ranging from about 0.04 to 0.6 m² in plan area) representing full size cross sections of the design by Pratt (1990) with an aggregate sub-base of relatively even size (around 50 mm), a laying course to support the blocks (originally 10 mm split pea gravel) and, importantly, a geotextile originally intended as a separating layer between the two aggregate layers. Brownstein (1998) was able to demonstrate the importance of the geotextile in retaining lubricating oil when applied in amounts in excess of the daily drip losses from even badly maintained vehicles. However a close inspection of his data indicates clearly that, although over 95% of the oil was retained initially, under these conditions, the ongoing absolute values of hydrocarbons in the effluents from below his model quickly became unacceptable with free product being released.

It was shown (Pratt *et al.* 1996) that in this model system, with the use of liquid inorganic fertiliser, biodegradation of

this oil could be stimulated, starting the remediation process and thus minimising the environmental harm. This was to the extent that it was possible to detect elevated carbon dioxide production, particularly just above the geotextile, for about three weeks following the nutrient application. After the carbon dioxide concentrations in the pavement had fallen close to ambient, further additional activity could be rapidly stimulated by adding more nutrients but this resulted in excessive losses of both N and P from the system.

The next project in this series was carried out by Bond (1999) who used far more realistic amounts of applied oil to mimic the effects of daily losses to a car parking surface. Again, wishing to speed up the biodegradation process in the long term, he utilised inorganic nutrients but, in this case, applied Osmocote slow release fertiliser pellets which were found to produce elevated carbon dioxide in his models for periods greater than 12 months following an initial application. The effective life of the applied fertiliser in this situation was longer than the declared life of the pellets when used for horticulture, indicating a degree of nutrient recycling within the biofilm once established. This phenomenon was studied further by Coupe *et al.* (2003) who identified a number of protozoan and metazoan species in the PPS environment which were known to contribute to nutrient cycling in natural environments. Coupe (2004) was also able to demonstrate that the protozoan community would evolve without an initial inoculation. Puehmeier (2009) reached the same conclusion with respect to bacteria.

Through the use of Osmocote pellets without micronutrients, Bond (1999) showed that initial biofilm formation was not limited by micronutrients which were provided by the materials in his model structure. He was also able to use a closed model system to obtain an idea of the fate of the oil applied to his system and illustrated clearly the importance of the geotextile in retaining the oil long enough for biodegradation to take place. He was also able to demonstrate that, in these very ideal circumstances, the half-life of the oil within the system was around 78 days.

Bond (1999) also investigated the release of excess inorganic nutrients from the base of his models and reported that the levels of N and P lost from the system were acceptable except for a very brief pulse when the nutrients were first applied. At that time, it was assumed that in realistic outdoor conditions external inputs from the environment would provide the required nutrients. This hypothesis was supported by the fact that, in the long term, the sanded joints between blocks in block paved surfaces could support plant life. In an attempt to study this further, Coupe (2004) found that in an outdoor model system in use as a live

University car park, the amount of nitrogen passing through the system was adequate to provide biofilm formation but that phosphorus was the limiting nutrient preventing adequate biofilm formation. The proposal made was that nitrogen was contributed by animal excreta, leaf fall, materials brought in on car tyres and in the gas phase as oxides of nitrogen from car exhausts. On applying Osmocote fertiliser pellets to the outdoor car park, it was found that the amounts of inorganic nutrients released from the system were worryingly high and far higher than reported by Bond (1999). The conclusion he reached was that this was thought to be caused by the crushing of pellets by the rocking motion of the pervious blocks (under traffic) between which they had been brushed. Later work by Nnadi (2009) however, has illustrated that this conclusion was probably wrong. After experiments using indoor models Nnadi *et al.* (2008) reported that not only did the models release larger amounts of inorganic nutrients than that reported by Bond (1999) but that by utilising this effluent for irrigation, the inorganic fertiliser could significantly enhance tomato and ryegrass production, when compared to plants irrigated with tap water that had been passed through control models. This would indicate a serious eutrophication potential if these effluents were to be released into surface waters. Why were these results so different from those of Bond (1999) even though as indoor model systems, they were not subject to crushing as proposed by Coupe (2004)? It probably was due to the fact that, wishing to be able to change the type of fertiliser at a later stage, Bond (1999) held his fertiliser pellets at the surface of the models in small nylon mesh baskets. This would tend to reduce nutrient release rates since they would rapidly dry out after rain events before the nutrients in the fertiliser came into equilibrium with the surrounding water. Nnadi's nutrients were applied in a far more realistic fashion with the Osmocote pellets exposed to water trapped within the infiltration channels for much longer periods.

Oil degradation activity in low nutrient situations

Work on geotextile based floating mat systems as secondary treatment devices in PPS installations has been reported by Puehmeier *et al.* (2004) and Puehmeier (2009). This included an attempt to compare fertilised (Osmocote) and unfertilised biofilm development where electron microscope studies were backed up by measurement of the ATP (adenosine triphosphate) content of the produced biofilms. It was shown that that whilst biofilm production was much less in the unfertilised situation, the organisms seemed to be

able to maintain a foothold on the geotextile by scouring whatever nutrients were available in the model system. However they did not have the capacity to initiate rapid biodegradation of hydrocarbons. Puehmeier (2009) was also able to demonstrate that, in a model system, a wide range of bacteria, of which 30% of the species identified were known oil degraders, were found after 3 months exposure to a mixture of lubricating oil, diesel and car wash detergent but without fertiliser addition. However the absolute numbers of oil degrading organisms was relatively low and rapid hydrocarbon degradation, as indicated by greatly elevated carbon dioxide measurements in the sub-surface atmosphere, was not observed. Adding Osmocote fertiliser towards the end of this experiment was shown to increase both carbon dioxide production and absolute numbers of oil degrading bacteria (Newman *et al.* 2004). The obvious next step seemed to be the incorporation of the limiting nutrients within the geotextile itself, delivering the nutrient at a carefully controlled rate and exactly at the right point. The ideal would be to provide a long-term supply as the living biofilm components actively scour the textile fibres to obtain the nutrients they require and yet avoid the release of excessive nutrients into receiving waters.

Self-fertilising geotextile-proof of concept

Spicer *et al.* (2006) reported studies which introduced the concept of the self-fertilising geotextile in PPS applications. The work was aimed at testing the concept of incorporating inorganic nutrients into the fibres of the geotextile. The geotextile fibres investigated were polymer fibres (either polypropylene or polyethylene) containing 1% by weight of nutrient releasing spherical beads (1.3 μm in diameter). These beads were deposited during the polymerization of a novel organic polymer in the form of spheres of uniform diameter. When soaked in ammonium phosphate/phosphoric acid solution for 30 min at 5 °C, they were shown to absorb 7% w/w of phosphate (in the form of ammonium phosphate). Upon contact with water, they were found to release this quickly but controlled slow release of phosphate was achieved when the beads were spun into polymer fibres. This reduced the equilibrium concentration of P in water which was in contact with the fibres to slightly less than 0.05 mg L⁻¹. This was considered to be a suitable level for sustained bacterial growth. The oil degrading activity in the system was measured by monitoring carbon dioxide concentrations in the atmosphere above the pavement. They also measured relative microbial activity (as measured by fluorescein diacetate hydrolysis (Schnurer & Rosswall 1982) in the

effluent from oiled model pavements after simulated weekly rain events. Spicer was able to demonstrate that the relative microbial activities in the models containing fertilised geotextile were more than double that of the unfertilised control after 9 weeks.

Whilst the organic micro-beads were successful in providing the nutrients required, the practical application proved to be problematic. The very high cost and poor availability of one of the starting compounds for the synthesis of the polymer beads was probably a significant factor in rejection of the material by the company sponsoring the work. Perhaps more importantly, it was found that there were inherent difficulties in the spinning process when attempts were made to incorporate these beads into geotextile fibres. This manifested itself in an unacceptable level of fibre breakage (Pers. Com., Paul Morris, AddMaster UK, 2009). This was particularly problematic if the additive concentration was increased to over 1% and given the relatively low P content of the beads, this could be an issue in long-term use. These studies did, however, illustrate that the principle of self-fertilising geotextiles was sound. Spicer (2006) later carried out some initial work on an alternative, inorganic, polymer additive. This additive was closely related to those previously used for adding antibacterial properties to bandages etc. The experiments reported here were carried out using an additive derived from that used in Spicer's later work. Since it had already been established that nitrogen would not be the limiting nutrient for biofilm establishment in pervious pavement situations, these experiments were targeted at providing P only.

One limitation of the work by Spicer (2006) was that although she was able to spin the modified fibres, she was never able to produce enough to create complete geotextiles. She carried out her experiments by placing a layer of loose fibres above a standard (Terram 1,000) geotextile. The work reported here however, has utilised complete geotextile samples. Spicer (2006) did have the advantage that her fibres also supplied N which meant, from a laboratory perspective, that her experimental arrangements did not require external N addition to replicate the availability of naturally available N from the wider environment.

EXPERIMENTAL

These experiments were carried out to determine whether the new additive would have the favourable properties reported for the organic spheres used by Spicer *et al.* (2006), in particular to investigate the initial rate of P release.

Using polypropylene fibres containing P releasing additive at 3% a sample of a needle punched geotextile was produced for experimental purposes. The additive is a finely divided inorganic phosphorus compound supplied by AddMaster UK Ltd. (Stafford, UK) and known as PM957. Comparisons were made with Inbitex (Hanson Formpave, Coleford, UK), a textile marketed as being suitable for biofilm maintenance but without a P releasing additive.

Preliminary tests

Rapid leaching test

One of the most important properties required of the self-fertilising geotextile is that it does not rapidly leach P to the extent that it produces unacceptable levels of P in the leachate. The ideal performance would be that the release of P was controlled by relatively slow kinetics whilst the fibres were in contact with a thin layer of water trapped on the geotextile, taking some time to approach equilibrium. This would mean that in the damp sub-surface environment, the fibres would release useful but limited amounts of P during non-rain periods but during rain events the water passing through the textile would, effectively, only be able to flush off the amount of P previously released and stored as soluble P on the surface of the geotextile since the last rain event. Dilution of the small mass of flushed-off nutrient by the stormwater would ensure that acceptable concentrations of P are released. The very simple experimental system consisted of a circular sample of the geotextile formed into a cone in a polyethylene filter funnels and 25 mL aliquots of water were allowed to drip through the funnels, once per day over a four day period. The combined sample was well mixed prior to analysis using ICP spectrometry. The reported limit of detection for P by the method used is 0.02 mg L^{-1} and none of the replicate samples produced concentrations that were detectable.

Bacterial inhibition test

Since the additive used was a new one, it was important to establish that the additive itself did not contain any substances which would directly inhibit bacteria. A suspension of *Pseudomonas putida* in saline was spread by means of a sterile swab over a number of plates of nutrient agar. About 5–10 mm square sections of textile test pieces were placed in the centre of each plate. The new geotextile and the control were each applied in triplicate. The idea of this test was to look for a zone of inhibition around the test

patch after incubating for 48 h at 30 °C. No evidence of inhibition was found in either the new or control geotextiles.

Longer-term leaching experiments

The aim of this experiment was to leach the samples of modified textile with water to remove the easily accessible P and then, after largely denuding the immediately leachable P, to subject the samples to a mild oxidation process to simulate the oxidation that would be expected to take place under the influence of microbial action and abrasion under a trafficked pavement over a long period in use. Nominally 1 g samples were sequentially extracted (without shaking other than a shake to mix prior to analysis) for periods ranging between 7 and 12 days in water (nominally 70 mL liquid per 1 g geotextile). The extractant was changed after each extraction. After the third extraction, when the new textile showed a greatly reduced leaching of P, the samples were soaked in 4 mL of dilute nitric acid (one part concentrated nitric acid to three parts water) for 7 days and then the sample was diluted to 70 mL with water and allowed to soak for 24 h. The samples were then analysed. This was repeated two weeks later with analyses being carried out as above. The Inbitex control textile was not found to release P above the detection limit even in the initial extraction stages where the release from the new textile was at its greatest.

Degradation study

Test rigs were constructed in the form of sealed microcosms incorporating full cross sections of pervious pavements (354 × 354 × 400 mm). The rig design was essentially a slightly larger version of the rig well illustrated in Spicer *et al.* (2006) except that the model pavements had a polymeric void forming unit to replace the usual stone subbase. They incorporated either modified or unmodified geotextiles both to form oil trap and separate the 10 mm laying course material from the void space. All models were inoculated with 250 mL of effluent drawn from an established pervious pavement model which had received oil for over 12 months at the start of the experiment. The experiment was carried out in triplicate.

Applications of 1.4 mL/m² used motor oil were made to the models every two weeks followed by a simulated 10 mm rain event. Artificial additions of inorganic nitrogen (as ammonium nitrate) at a rate of 0.05 g/m²/rain event were also made along with the simulated rainwater. This was intended to simulate the inputs of nitrogen from external

sources that have previously been shown to be naturally occurring in a real PPS application. The degradation of oil was again followed by monitoring the carbon dioxide concentration in the headspace of the models using samples drawn from the models by syringe. Certified calibration gases (BOC Special Gases Ltd.) were used for calibration of the IR analyser. After each sampling event the lids of the models were removed for rain simulation and the air in the headspace of the box was displaced by ambient air so as to simulate the regular replacement of air above a pavement surface. Vouchers of clean geotextile were placed within the models at the start of the experiment to allow sampling of the textiles for electron microscopy studies of the growing biofilm. This was carried out as soon as a strong visible biofilm was observed. After air-drying for 48 h at 30 °C and fixing in formaldehyde vapour for 48 h, the samples were mounted on aluminium stubs using conductive sticky pads. The samples were palladium coated by sputtering and then examined by scanning electron microscopy.

RESULTS AND DISCUSSION

Table 1 demonstrates that during the extended extraction experiment, the amount of P released from the new geotextile started with a large initial release but rapidly fell to relatively low levels. However, following the initial mild oxidation step aimed at simulating the role of microbial exudates produced within a growing biofilm the amount extracted was 8 times higher than the previous extraction. A similar boost in P release was seen after the next oxidation step. This indicates that large amount of P trapped within the polymer was only being made available when actively

Table 1 | Mass of P extracted per g of self-fertilising textiles during extraction in water before and after mild oxidation steps (nd, not detectable)

Days from start of experiment	New textile µg/g P extracted mean <i>n</i> = 40	Standard error	Max.	Min.
7	28	0.6	34	21
19	5.5	1.1	34	2.0
26	1.8	0.2	5.5	0.4
<i>Mild oxidation step during this period</i>				
34	16	0.8	44	0.8
40	0.5	0.2	7.5	nd
<i>Mild oxidation step during this period</i>				
47	2.7	0.1	4.0	nd

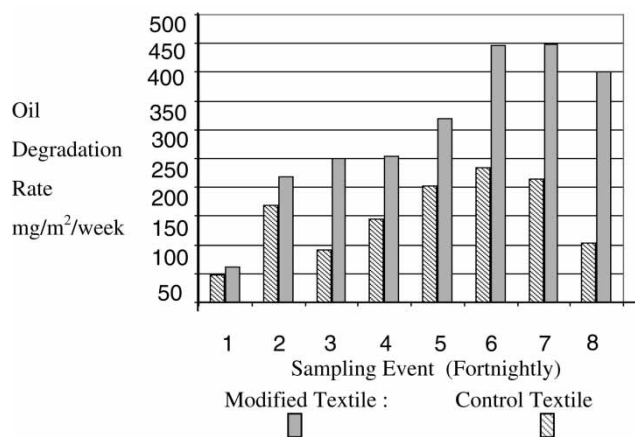


Figure 1 | Oil degrading performance of the modified textile compared with the control textile ongoing/medium scale experiment-mean values $n = 3$.

scoured by microbial activity. It should be noted that even under the artificially long contact conditions used in this experiment, the highest mean concentration of P for any extraction step was 0.5 mg/L and after four extractions, the mean concentration was 0.2 mg L⁻¹ even though the fourth extraction followed an oxidation step in dilute nitric acid.

The results of the degradation experiment are shown in Figure 1. The data presented here is in the form of calculated mass of oil degraded per unit area per week during the preceding fortnight and again illustrates that over the period of the experiment, a significantly enhanced biodegradation rate occurred on the new geotextile when compared to the unmodified control.

After approximately 30 days, a very strong visible biofilm was found on the new geotextile vouchers in the models but was not present in the control models after 60 days. Electron micrographs presented in Figure 2 show examples of the development of both bacterial

(Figure 2(a)) and fungal (Figure 2(b)) oil degrading organisms on the modified textile.

CONCLUSIONS

Whilst the ongoing work will provide greater understanding of the long-term performance of this new geotextile, the key conclusions of this work are as follows:

- Using the new additive, it is possible to create geotextiles with a P additive content of at least 3% without compromising production capabilities.
- Release rate of P from the modified geotextile appears to be at levels capable of supplying enough P to promote oil degrading biofilm growth, but are below concentrations that would adversely affect water quality.
- In the absence of externally added P, the modified geotextile supports both biofilm formation and oil degradation.
- During simulated service conditions, partial oxidation of the textile fibres has a positive effect on the leaching of P; leading one to consider that the long term controlled release of P is likely.

The overall conclusion of the experimental work carried out to date is that, at this stage of the investigation, the new geotextile shows the behaviour that would be expected of a geotextile designed to supply the phosphorus required to initiate and stimulate active oil biodegradation over the long-term life of a pervious pavement. Whilst Spicer (2006) demonstrated the effectiveness of self-fertilising geotextiles using organic polymer additives, this new inorganic additive seems to be a solution to the production problems which does not compromise the P releasing properties. Work is ongoing to create a greater confidence in the longer-term performance of the modified geotextile with the next step

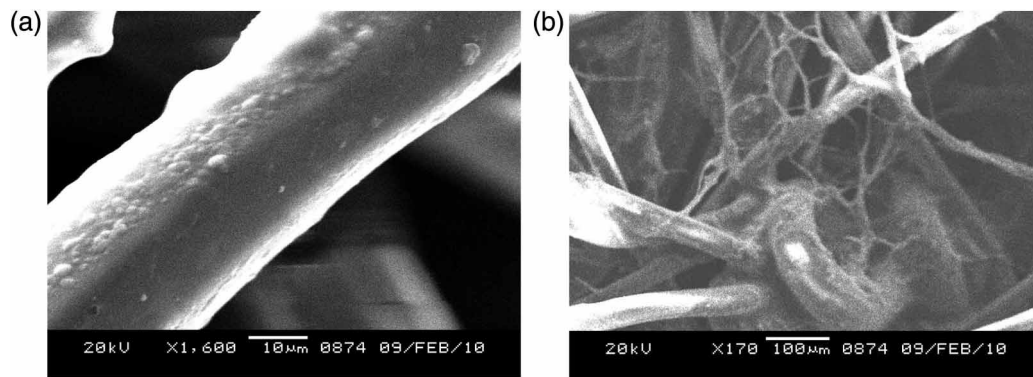


Figure 2 | Scanning electron micrograph of novel geotextile after 5 weeks incubation. (a) Single fibre showing bacterial film: (b) Fungal hyphae growing between fibres.

intended to include a deeper study of the microbial ecology of biofilms formed on the new textile.

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REFERENCES

- Altas, R. M. 1981 Microbial degradation of petroleum hydrocarbons: an environment perspective. *Microbial. Rev.* **45**, 180–208.
- Atlas, R. M. 1984 *Petroleum Microbiology*. Macmillan Publishing Company, New York, pp. 1–618.
- Atlas, R. M. & Bartha, R. 1972 *Degradation and mineralisation of petroleum in sea water: limitation by nitrogen and phosphorus*. *Biotech. Bioeng.* **XIV**, 309–318.
- Bond, P. 1999 *Mineral Oil Biodegradation Within Permeable Pavements: Long-Term Observations*. PhD Thesis, Coventry University, England, UK.
- Bragg, J. R., Prince, R. C., Horner, E. J. & Atlas, R. M. 1994 Effectiveness of bioremediation for the Exxon-Valdez oil spill. *Nature* **368**, 413–418.
- Brownstein, J. B. 1998 *An Investigation of the Potential for the Biodegradation of Motor Oil Within A Model Permeable Pavement*. Unpublished PhD Thesis, Coventry University, Coventry, UK.
- Coupe, S. J. 2004 *Oil Biodegradation and Microbial Ecology within Permeable Pavements*. Unpublished PhD Thesis, Coventry University, Coventry, UK.
- Coupe, S. J., Smith, H. G., Newman, A. P. & Puehmeier, T. 2003 Bio-degradation and microbial diversity within permeable pavements. *Eur. J. Prot.* **39**, 495–498.
- Frankenberger, W. T., Emerson, K. D. & Turner, D. W. 1989 *In situ* bioremediation of an underground diesel fuel spill: A case history. *Environ. Manage.* **13** (3), 325–332.
- Gruiz, K. & Kriston, E. 1995 *In situ* bioremediation of hydrocarbon in soil. *Soil Sediment Contamination* **4** (2), 163–175, 1549–7887.
- Kämpfer, P., Steiof, M. & Dott, W. 1991 Microbiological characterization of a fuel-oil contaminated site including numerical identification of heterotrophic water and soil bacteria. *Microb. Ecol.* **21**, 227–251.
- Newman, A. P., Puehmeier, T., Schwermer, C., Shuttleworth, A., Wilson, S., Todorovic, Z. & Baker, R. 2004 The next generation of oil trapping porous pavement systems. *5th International Conference Sustainable Techniques and Strategies in Urban Water Management, Lyon, France, Groupe de Recherche Rhone-Alpes sur les Infrastructures et l'Eau, NOVATECH, 6–10 June 2004, GRAIE, Lyon, France*, pp. 803–810.
- Nnadi, E. O. 2009 *An Evaluation of Modified Pervious Pavements for Water Harvesting for Irrigation Purposes*. Unpublished PhD Thesis, Coventry University, Coventry, UK.
- Nnadi, E. O., Newman, A. P. & Puehmeier, T. 2008 An Evaluation of the use of stored water derived from permeable paving systems for irrigation purposes. In *Proceedings of the 11th International Conference on Urban Drainage, August 31–September 5, 2008, Edinburgh, UK*.
- Pratt, C. J. 1990 Permeable pavements for stormwater quality enhancement. In *Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined Sewer Technology* (H. C. Torno, ed). Am. Soc. Civil Eng., New York, pp. 131–151.
- Pratt, C. J., Mantle, J. D. G. & Schofield, P. A. 1995 UK research into the performance of permeable pavement reservoir structures in controlling storm water discharge quantity and quality. *Water Sci. Tech.* **32**, 63–69.
- Pratt, C. J., Newman, A. P. & Brownstein, J. 1996 Bioremediation processes within a permeable pavement: initial observations. In *Proceedings of the Seventh International Conference on Urban Storm Drainage, September 9–13, 1996, Hannover, Germany*.
- Pratt, C. J., Newman, A. P. & Bond, P. C. 1999 Mineral oil biodegradation within a permeable pavement: long term observations. *Water Sci. Tech.* **39**, 103–109.
- Puehmeier, T. 2009 *Source Control Devices Used in Sustainable Urban Drainage for Hard Paved Areas*. Unpublished PhD Thesis, Coventry University, Coventry, UK.
- Puehmeier, T., Coupe, S. J., Newman, A. P., Shuttleworth, A. & Pratt, C. J. 2004 Recent developments in oil degrading pervious pavement systems-improving sustainability. In *Proceedings of Fifth International Conference on Sustainable Techniques and Strategies in Urban Water Management, NOVATECH, 6–10 June 2004, GRAIE, Lyon, France*, pp. 811–818.
- Schnurer, J. & Rosswall, T. 1982 Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and litter. *Appl. Environ. Microbiol.* **43**, 1256–1261.
- Spicer, G. E. 2006 *The Development of A Self-Fertilising Geotextile Incorporating Slow Release Phosphate Beads for the Maintenance of Oil Degrading Bacteria in Permeable Pavements*. Unpublished PhD Thesis, Coventry University, UK.
- Spicer, G. E., Lynch, D. E., Newman, A. P. & Coupe, S. J. 2006 The development of geotextiles incorporating slow-release phosphate beads for the maintenance of oil degrading bacteria in permeable pavements. *Water Sci. Technol.* **54** (6–7), 273–280.
- Swannell, R. P. J., Lee, K. & McDonagh, M. 1996 Field evaluations of marine oil spill bioremediation. *Microbial. Rev.* **60**, 342–365.