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Enhancement of Oil Retention and Biodegradation in Stormwater Infiltration Systems

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ABSTRACT

This paper reports recent developments in oil trapping and oil biodegrading systems in pervious pavements and in infiltration systems used in conjunction with non-pervious surfaces. The advances made in the technology and operation of pervious surfaces fitted with an integrated oil water separator will be described. This involves a newly developed, floating mat system which serves to interact with any oil which, in the event of a large spill, passes through the initial oil retaining structures of a pervious pavement or other form of infiltration system (see Puehmeier et al., 2004). It also provides the ideal surface upon which the oil degrading organisms will thrive. The ability of these enhanced systems to produce a diverse biodegrading bacterial/fungal community is reported. A further study will report a comparison of biodegradation of new and used mineral oil trapped on these structures. The second area of research reported will be associated with a novel oil separating system designed to be either coupled closely to an infiltrating filter trench which can be used in conjunction with impervious surfaces or to direct the water back under an impermeable surface for further treatment, retention and attenuation of flow. This system was shown to be highly effective in removing hydrocarbons and has the advantage that it can be used as a retrofit solution to allow disconnection of existing impervious surfaces without exposing groundwater to contamination.

KEYWORDS

drainage & irrigation/pavement ; design/pollution ; oil separation/retention; biodegradation

INTRODUCTION

Retention and biodegradation of oil in pervious pavement (PP) systems has been reported previously both in laboratory studies (Newman et al., 2002(a) & 2002(b), Coupe et al., 2003) and field studies (Brattebo and Booth, 2003). Oil retaining capabilities of some block paved PP systems have been shown to be more than capable of adsorbing the amounts of oil arising from the regular daily drips of vehicles in a car park (Pratt et al., 1999). However at higher oil loadings the oil retaining capability of these systems has been shown to fail under certain circumstances (e.g. Puehmeier et al., 2004). A response to the need to protect the environment from relatively large spillages was the development of a closely coupled pavement/oil separating system which allows post infiltration-separation of oil from polluted infiltrated stormwater. Wilson et al. (2003) demonstrated the performance of such a system when constructed with proprietary polypropylene load bearing/storage elements used in an attenuation- rather than an infiltration format. This device is currently marketed under the name Permaceptor®. The oil retaining performance of this system was shown, in shockloading conditions, to be much better than that reported by Puehmeier et al. (2004) for the performance of polymeric cellular based systems constructed without the oil/separator configuration. It has also been demonstrated (Newman et al., 2004) that oil biodegradation was significant within the oil trapping systems and that the degrading capabilities were enhanced by adding inorganic nutrients. This work also showed that the rate of biodegradation of oil was a function of the population of oil degrading bacteria content of the free body of water. Both oil degrading bacteria and inorganic nutrient concentrations are subject to considerable fluctuation in storm conditions. Both microorganisms and nutrients (including free nutrients and those tied up in biomass) will be lost at each rain event, potentially reducing the capability of the system to operate without significant inputs. Another issue is the eventual formation of flocculated bodies of oily matter which might be either lost from the system or clog the geotextile filters at the outlet. This has been recently addressed by the development of a floating mat device which will interact with the free product oil, allow the formation of a biofilm on a solid surface and provide the opportunity for nutrient recycling which would allow active biofilm development in the absence of regular nutrient inputs. The system is intended to provide an environment which is ideal for the encouragement of oil degrading microorganisms where moisture, oil and oxygen from the atmosphere are all available in a situation supplied with a large surface area for oil adsorption and biofilm attachment. The floating mats (see figure 1) consist of an upper sorptive layer of geotextile (Terram 1000®) bonded to a lower floating layer of LDPE grid which is buoyant due to the introduction of a blowing agent in the moulding process (Boddingtons Limited, Essex, UK). These mats are cut to the intricate shapes required to allow them to float freely inside the plastic load bearing boxes (Culleton et al., 2005) by means of a laser cutting device.

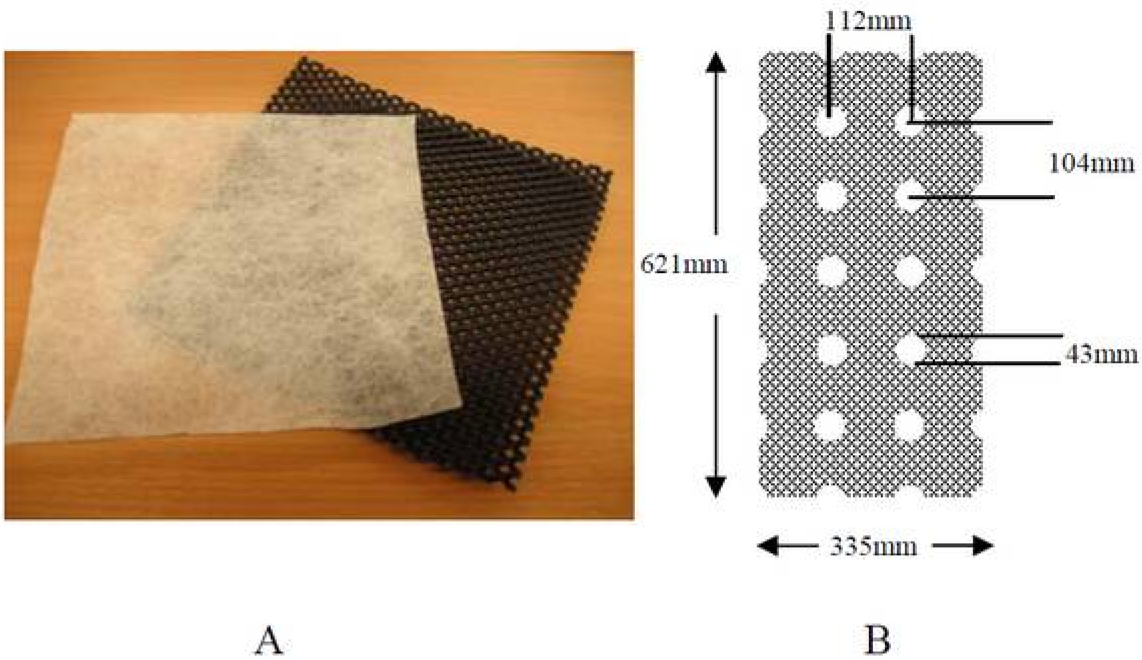


Figure 1:

A) Components of the floating mat, Terram 1000® geotextile and HDPE grid

B) Profile used for installation into Permavoid® geocellular units

A problem associated with pervious surfaces of all types is the reluctance by some developersto make use of them. Another important issue is that, in a retrofit situation, the need to disconnect drainage may well not be sufficient to justify re-laying large areas of paved surface. Indeed pervious pavements are proposed by Stovin and Swan (2003) as a poor economic option for SUDS retrofit.

These factors defined the need to create a system which could be used in conjunction with impermeable surfaces and with the flexibility to use for both new-build and retrofit purposes. It is necessary that the system retains much of the hydrocarbon and suspended solid removal capabilities of a pervious pavement. As well as being used in conjunction with a subpavement storage volume allowing either infiltration or attenuation/further treatment under a new paved surface the system is a potentially attractive pre-cleaning device prior to a sand filter which could be constructed either as a continuous trench or at intervals along the boundary of a paved area such as a car park and allowed to infiltrate water directly into the ground. The device which was developed was based on a kerb drain where, instead of the water being conveyed linearly along the drain, the water would be transmitted at right angles to the drain into a downstream infiltration or attenuation device via a proprietary oil/water separation system. This device has gone through a series of development stages and the testing reported is upon an earlier form of the system before the development of the current system which is much more amenable to mass production. Several practical applications of this device have been reported by Culleton *et al.* (2005) which also contain useful detailed diagrams for further reference.

THE FLOATING MAT DEVICE

The studies on the floating mat device were aimed at establishing a number of basic parameters. This included the extent and nature of the biofilm formed and in particular the difference in response between situations where inorganic nutrients were artificially provided and situations where they were not. In such circumstances the floating mat would take advantage of the ability of the system to form a solid-supported biofilm which is known to facilitate the local recycling of limited amounts of inorganic nutrients particularly when large protozoa and multicellular organisms are present (Kahlert and Baunsgaard, 1999). These could then be supplied either by natural sources or very slow release fertiliser systems and thus reduce the need for repeated nutrient addition.

In these static water experiments rectangular test pieces of floating mat were used and the experiments were carried out in simple modified rectangular HDPE food containers (240 mm x 240 mm x 80 mm) with ports drilled in the lid to allow the insertion of rubber Suba seals (William Freeman Ltd, Barnsley, UK) to act as septa. CO2 was measured in these chambers after sampling with a syringe through the septum followed by measurement on a NDIR system (225-MK3, ADC BioScientific Ltd., UK). An oil loading of 163 g/m2 was used in all cases and in those models supplied with inorganic nutrients they were supplies as Osmocote plus slow release fertiliser pellets at a rate of 135 g/m2. The test chambers were incubated in the dark at 20 °C. Samples were cut from the floating mat after 9 weeks and subjected to scanning electron microscopy to study the extent and nature of biofilms formed in these conditions. Further microbiological studies on the organisms forming the biofilm were also carried out using ATP measurements and the PCR/DGGE process described previously (Newman *et al.*, 2002(b)) in an attempt to establish whether or not the dominant organisms (only bacteria targeted with selected primers) growing on the mat were different from that of oil degrading organisms developing in liquid phase culture given that the inoculum (taken from an actively oil degrading PP model) was the same in all cases. For the analysis the of DGGE bands that were detected and dendrograms were constructed by simple matching of unweighted pair groups with mathematical averages using the PHYLIB program (version 3.61) (Felsenstein, 1989). It was also intended to study the differences in responses to used and unused oils. Previous studies on stone based systems had indicated that used oils tended to biodegrade more slowly than new oils (Lowe, 2005). A static water experiment, under the high nutrient conditions described above, was therefore carried out to compare the carbon dioxide evolution rates. As with all these static water experiments the air in the sealed biodegradation chamber was changed after each CO2 measurement to set the CO2 concentration back to the ambient condition.

THE OIL SEPARATING KERB/CHANNEL DRAIN

In the particular version of the system used in this experiment the kerb drainage elements were intended to be linked such that the entire length of the drainage system is used as stilling chamber to spread out the oil. The experimental design was such that it represents a situation in which a major hydrocarbon spillage occurs simultaneously in every single car parking bay on the car park and that all spillages occur 1.0 m from the kerb edge through which the water enters the combined channel/sand filter system.

Test Apparatus

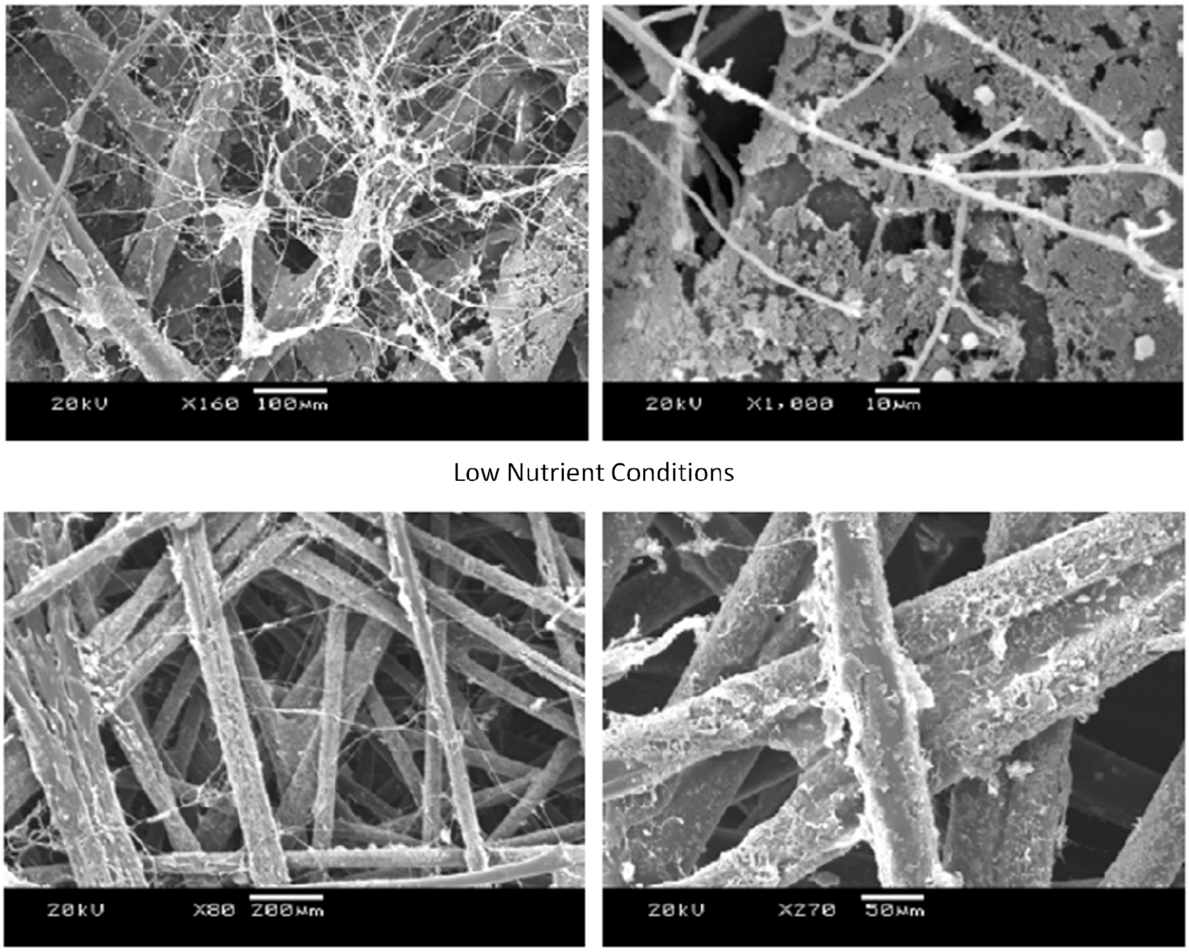
The test apparatus used was a cross section of the installation described by Culleton et al.(2005) with a 0.6m wide poured concrete surface feeding the oil separating channel drain and discharging into a sand filter (0.6 m2 area, with a depth of 0.7 m). In the laboratory situation the sand filter cross section was constructed in a welded polyethylene chamber which was reinforced with a metal frame and fitted with an acrylic front panel to allow observations of the water movement. Adjacent to the sand filter and feeding into the sand filter via a geotextile covered slotted pipe was the proprietary oil separation system which accepted the drainage from the 1.5m long poured concrete slab with a 1 in 80 fall. Artificial rain was supplied as tap water. A rainfall simulation device of a type previously described (Pratt et al., 1999) was installed such that the raindrops fell 1 m before falling directly onto the oiled surface. At the up-gradient extreme of the 1.5 m long cross section there was provision for application of additional water to represent the sheet flow over the surface of the parking bay not contaminated by oil but contributing to the flow and capable of lifting the oil from the surface and carrying it into the modified kerb drain. The system was fitted with sampling valves to collect the effluent at two points one just after the pre-cleaning device and one after the sand filter.

The flow rates for both sources of water were set to simulate a rainfall rate of 13 mm per hour with direct rainfall and sheet flow from up-gradient being supplied in the ratio 1:4. The system was allowed to prime for 30 minutes. A 2.9 litre aliquot of lubricating oil (Shell Rimula Super SAE 15W-40) was applied from a funnel with a 1.3 cm diameter orifice from a height of 30 cm whilst continuing to apply the rain. This application was continued for approximately 1,125 minutes extracting 1 litre grab samples from a side arm sampling bypass (which directly sampled the outflow from the oil separator without entering the sand filter) and from the sand filter base as appropriate (shown as Pre-Treatment and Full-Treatment respectively in table 1).

RESULTS AND DISCUSSION

Floating Mat

There were considerable differences in both the structure and density of the biofilm when high and low nutrient conditions are compared. However the low nutrient condition, without the addition of inorganic fertiliser still results in an almost continuous biofilm which could only be obtaining energy from the degradation of oil. It can be seen from Figure 2, which shows biofilm growing on and between the fibres of the Terram 1000® geotextile under both high and low nutrient conditions, that there are considerable differences in both the structure and density of the biofilm when high and low nutrient conditions are compared. However the low nutrient condition, without the addition of inorganic fertiliser still results in an almost continuous biofilm which could only be obtaining energy from the degradation of oil. Measurement of ATP concentrations, a measure of biomass, which reflects the cellular energy currency of the biofilm, showed that the high nutrient biofilms were around 30 times denser than the lower nutrient biofilms. CO2 measurements indicated that, under low nutrient conditions, there was enhanced degradation rate of oil when compared to oil free floating on a water body. This is also reflected in the DGGE results shown in figure 3.



High Nutrient Conditions

Figure 2. Electron micrographs of samples of Terram 1000® layers from floating mat after 9 weeks exposure to oil (163 g/m2) under high and low inorganic nutrient conditions.

The macroscopic behaviour of the oil was also very different between chambers equipped with the floating mat and those without. In the non-floating mat boxes the oil quickly became partially emulsified and forms large flocks of material with density close to and sometime greater than that of the water particularly when nutrient levels were high. This phenomenon was absent from all floating mat chambers, whether dosed with added nutrients or not.

Figure 3 illustrates that, taking into account the banding patterns of both biofilm (s) and water body (l), the DGGE results show an apparently more diverse bacterial community in the low nutrient-floating mat chambers compared to all other chambers. The species distance map shows that under high nutrient conditions the species that are present on the floating biofilm are very similar to those in water body. However under low nutrient conditions there is a significant difference between the species present on the floating mat and those present within the water body. This indicates an advantage for biofilm formed under low nutrient conditions since the organisms selected will be maintained as part of the floating biofilm and not washed away during large rain events. Figure 4 shows the results for the comparison of used and unused engine oil. This experiment produced an unexpected result since it was believed at the time that substances present in used oil may inhibit the organisms responsible (Lowe 2005).

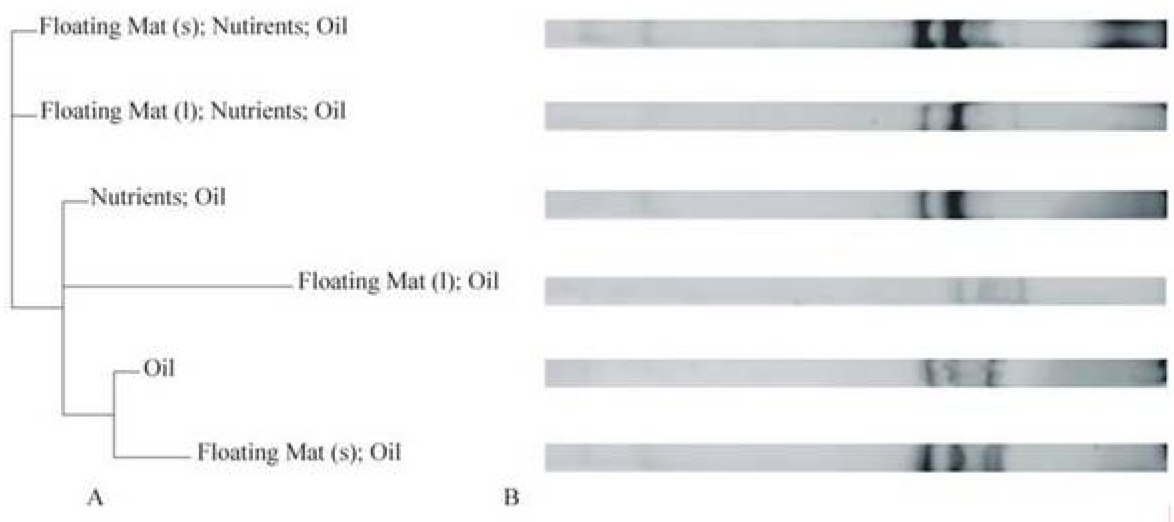


Figure 3. A) Dendrogram showing the relatedness of the DGGE banding patterns. B) DGGE analysis of 16S rDNA fragments from water and solid surface samples obtained 9 weeks after the start of the experiment.

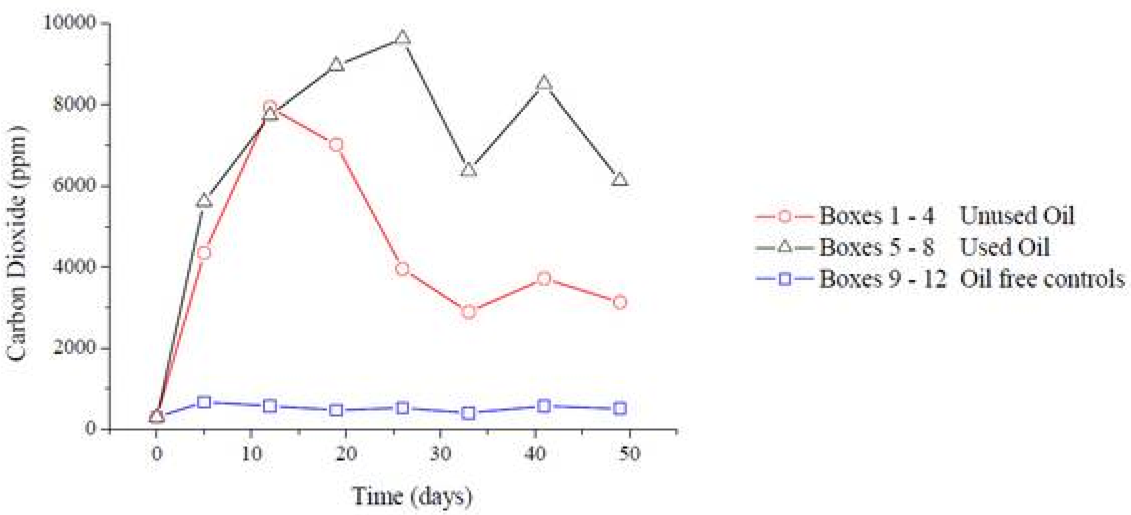


Figure 4. Comparison of mean carbon dioxide concentrations for used and unused oil on floating mats. n=4 for each treatment. Mean values used.

Kerb/Channel Drain

The kerb drain test bed was equipped with an acrylic window to allow observation of the oil and water within the modified kerb drain. The visual observation of the 40 mm thick oil layer corresponded well with the anticipated thickness taking into account the volume of oil added and the surface area of the channel. The water was seen to pass through this layer without disturbing the surface, due to the low flow velocities in the system. Table 1 shows the oil and grease concentrations measured in the samples collected. It is worth pointing out here that had all the oil been lost during the experiment the average concentration would be around 1,000 mg/l. If it had been lost over 15 minutes (the approximate time for all the applied oil to enter the kerb drain) the concentration would have been around 70,000 mg/l. The median output concentration from the pre-treatment part of the system was 1.3 mg/l. Under the, admittedly, unrealistic conditions reported in this test, and assuming no maintenance of the system, it would take over 1.5 years of continual rain at 13mm/hour to release all the oil into the filter.

Table 1. Output concentrations of Oil and Grease for grab samples taken from pre-treatment and full treatment sampling ports

Amount of Treatment	**Sample Time from oil addition (minutes)**	**Oil and Grease mg/l**
Pre-Treatment	0	1.3
Pre-Treatment	13	1.7
Pre-Treatment	30	1.3
Pre-Treatment	45	2.7
Pre-Treatment	60	0.8
Pre-Treatment	120	0.9
Pre-Treatment	158	0.6
Full-Treatment	127	1.5
Full-Treatment	143	0.1
Full-Treatment	189	0.8
Pre-Treatment	1125	0.1

Several of these systems have been installed both in the form of a continuous kerb drain and in the form of discontinuous channel drains which are easier to install and have some maintenance advantages. The systems have included infiltration systems installed beyond the edge of the drained area and both infiltration and attenuation systems in which water is stored below the paved area. Some sites have facilities for monitoring the effluents produced and passage of oil beyond the pre-filter stage has not been observed (Culleton *et al.*, 2005).

CONCLUSIONS

The floating mat device is probably capable of considerable optimisation, particularly in relation to the selection of the upper geotextile layer. However it can be concluded that:

• The floating mat device offers additional confidence, when required, that hydrocarbon spillages can be satisfactorily contained and biodegraded in stormwater attenuation and infiltration systems provided with a permanent pool of water.

• The presence of an oil degrading biofilm on the floating mat has been demonstrated and the system has been shown to biodegrade used oil better than unused oil.

The ability of these systems to work where the water storing void is regularly drained is currently under study. In relation to the oil separating kerb/channel drain the following can be concluded:

• The kerb/channel drain devices can act as pre-cleaning devices to essentially replace the filtration effect of a pervious pavement and whilst it probably does not offer all of the advantages of direct infiltration through the paved surface it can be an attractive alternative when pervious paving is not considered suitable.

• It probably has a shorter maintenance interval than would be necessary with a pervious surface but the ability of an operator to respond to large oil spillages before the contaminant actually gets underground, beyond relatively easy recovery, is an advantage that should be considered.

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The concept of integrating the oil interceptor into a pervious pavement, the geo-cellular units, the oil separating kerb/channel drain and the 'Floating Mat' described in the paper are subject to patent applications.

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