Performance of an enhanced pervious pavement system loaded with large volumes of hydrocarbons

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ABSTRACT

Five litres of lubricating oil and two 8.5 litre batches of diesel were deposited on each of two hydraulically isolated experimental enhanced pervious pavement parking bays. The 50 mm aggregate subbases of the two bays were of either recycled concrete or crushed limestone. The bays were constructed in such a way that a near-surface gravity separator was created by the arranging of the outlet pipes such that a permanent pool of water was maintained in the system and water could only enter from below the level of any floating oil. Dissolved/dispersed hydrocarbons were measured at acceptable concentrations when monitoring was carried out over a period of approximately 5 months. The maximum concentration was 7.2 mg/l and of all the samples collected only 3% exceeded the 5 mg/l limit applied in the UK for a class 1 interceptor, and the majority of samples had hydrocarbon concentrations of less than 2 mg/l. Much more significant is the fact that no free product was discharged from either system up to the time the experiment was dismantled 2 years from the first oil application despite the fact that sufficient hydrocarbon had been added to each pavement to produce a film on a water surface of over 500 hectares.

Key words | hydrocarbons, pervious pavements, sustainable drainage systems

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INTRODUCTION

Large areas of urban impervious surface are most commonly associated with automobile use, particularly parking (Brattebo & Booth 2003). The environmental effects of motor vehicle parking areas include impacts on the water environment. Pervious pavement systems offer one solution to the potential problem of increased urban runoff (Barbosa *et al.* 2012; Freeborn *et al.* 2012) and thus decreased stream water quality associated with automobile usage (Brattebo & Booth 2003; Woods-Ballard *et al.* 2007; Mitchell *et al.* 2012) In pervious pavement systems water can be either allowed to soak naturally into the underlying soil (infiltration systems) or stored for controlled release to a watercourse (attenuation systems). In both processes stormwater is subject to a number of pollution retention and degradation mechanisms (Puehmeier *et al.* 2005; Newman *et al.* 2011). The choice of whether to use infiltration or attenuation to manage the stormwater will depend largely on the suitability of underlying soils for infiltration. The storage/load bearing element of a pervious pavement system is traditionally an aggregate subbase using a relatively uniform size range (Pratt 1995), but plastic box void forming systems are available including some which can be used sufficiently close to the surface to form a complete subbase replacement as well as providing a storage void (Wilson *et al.* 2003; Culleton *et al.* 2005). Pervious pavement systems can play a significant role in mitigating the impacts of stormwater runoff caused by urban development (MacDonald & Jefferies 2001; Schlüter & Jefferies 2001; Dierkes *et al.* 2002; Fach & Dierkes 2011). This has included the retention and biodegradation of oils. A review paper by Scholz & Grabowiecki (2007) summarises these capabilities in addition to the numerous other potential advantages of pervious pavement systems. However, the oil-retaining capabilities of pervious pavements are not unlimited. This was illustrated clearly in an experiment which was carried out by our group as a response to the fact that a set of full-scale pervious pavement test beds previously used by the authors was to be destroyed by building works (Newman *et al.* 2004a). It was clear that the loss of the complete oil sump contents from a large vehicle would totally overwhelm the oil-retaining mechanisms within the pavement. Alongside these experiments work was underway to develop

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an enhanced pervious pavement system with a near-surface gravity separator incorporated into the subbase (Newman 2002; Wilson *et al.* 2003). The enhanced system works by maintaining a pool of water within the subbase and only allowing water to escape from below the expected level of any floating oil. The means by which this can be achieved is dependent on the nature of the load bearing/water storage element and whether the system is acting in an infiltration or attenuation mode. For plastic box based systems the construction of a baffle and weir arrangement created by welding polyolefin membranes in appropriate positions (see Wilson *et al.* 2003) proved to be the most practical. For pavements based on aggregate subbases, as the patent document (Newman 2002) indicated, the permanent water pool could be achieved by means of judicious arrangement of impermeable membranes within the subbase (Newman *et al.* 2004a). However, in practice, it was found to be easier to arrange this in attenuation systems by the use of outlet pipes in which the entry to the outlet pipe is restricted to below the level of the discharge. This system performed remarkably well in laboratory studies (Wilson *et al.* 2003; Newman *et al.* 2004a), but no reports have previously been made on field-scale studies of this enhanced design.

MATERIALS AND METHODS

The test bed was constructed at Bury, Lancashire. The site of the installation was selected partly because the topography of the site had particular advantages. The new installation could be constructed on steeply sloping ground. This allowed the collection of samples as effluent emerged from pipe work exiting the face of the retaining wall required to allow construction of a level parking area. Figure 1 shows a schematic of the cross-section for the test bed and Figure 2 is a photograph of the site during construction. Access to carry out sampling and other operations was found to be far more convenient than the sub-surface sampling chambers that had previously been required at the relatively flat site, which this installation replaced. The layout of the new site also provided space for the interception and storage of the effluents in 1 m^3 tanks (intermediate bulk containers) to allow the quarantined water to be examined and (if necessary) analysed before the rainwater was discharged. The intention here was that when any of the pervious pavement test beds were subject to artificial oil dosing (or serious accidental spills) effluent with significant free product could be quarantined prior to being taken away by tanker for treatment.

As indicated, the test bed installation was constructed on a slope (approximately 30 degrees to the horizontal). A concrete retaining wall was constructed (on a concrete foundation – not shown in the schematic) from precast units (2.5 m high). In total 40 units were used to create a retaining wall approximately 40 m long butting up to an existing concrete ramp on one side and cut into the existing fall of the valley side on the other. Figure 2 illustrates the general topography of the site, with an added white horizontal line indicating the position of finished parking surfaces.

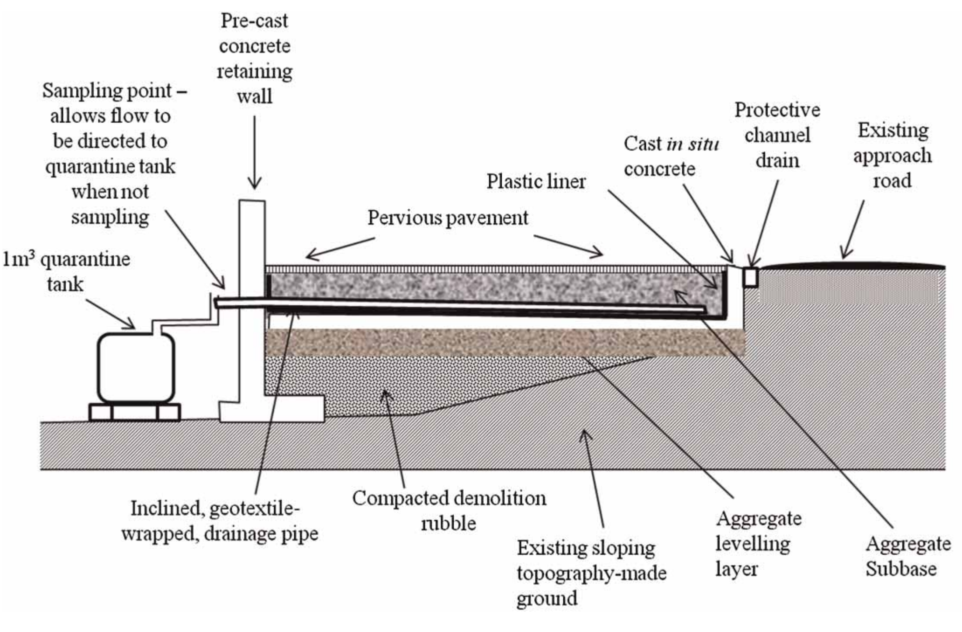

Figure 1 | Schematic cross-section of test rig (not to scale).

Figure 2 | The site at the start of the construction phase.

Behind the retaining wall the void was partly filled with compacted demolition rubble up to a depth of 750 mm from the lip of the wall. Compacted aggregate was then used as a levelling layer prior to laying a 50 mm thick concrete bed. Some 4.8 m from the front face a rear wall was cast *in situ* to terminate at finished levels. Similarly, dividing walls (at intervals depending on whether double or single bays were required) were cast *in situ* to finished levels. The front retaining wall was penetrated as appropriate for the entry of required pipe work. Surface water was prevented from flowing onto the test bed area by a retaining wall at each end and a continuous channel drain run between the test bed and the existing approach road. This supplementary drainage system discharged onto the unpaved surfaces down-valley of the site. All chambers were lined with a sacrificial welded polyethylene liner which is discarded whenever a new experiment is established. The experiment reported here was based on two of the available individual bays, which were constructed with aggregate subbases and provided with an outlet pipe arrangement extracting water from below the surface of a permanent pool of which water was maintained in the subbase. These experimental systems were single-bay car parking areas of dimensions 2400 mm × 4800 mm. One was constructed using 50 mm limestone aggregate as the subbase and the other with 50 mm recycled concrete. The subbases were 470 mm deep. The wearing courses consisted of Formpave Aquaflow blocks and were both supported on a laying course of 6–10 mm limestone with a Terram 1000 geotextile layer between the laying course and subbase. The outlet pipe was 100 mm diameter uPVC and ran the full length of the centre of the bay. It was capped at the upstream end and was perforated on the lowest part of the circumference only up to within 0.5 m of the front wall. The slope of the pipe away from the outlet was such that all the holes were just below the level of the final discharge. It would have been possible to raise the water level in the subbase by means of a small weir arrangement at the discharge point but this was not required. The pipe was wrapped in Terram 1000 geotextile. The experimental parking bays were subject to experimental contaminative processes 1 week after completion of construction. Except for the first 2 days of the experiment, when the pavements were subject to artificial rainfall, monitoring was restricted to days when a scheduled visit to the site coincided with a situation where the pavements were discharging effluent. Resources were not available for more frequent visits to the site or for continuous automated sampling. This resulted in a discontinuous sampling regime with periods between sampling of up to 19 days. This was mitigated by the fact that effluent was continually retained to allow for subsequent analysis of combined effluent and continual observations for free product release.

In experiments carried out alongside this work it was observed that loss of calcium salts from recycled-concrete pervious pavement system models caused effluents to have pH values up to 11.5, and even from limestone subbases a pH of over 8 is typical. If a calcareous subbase is adopted it would be important to ensure that any effluent standards for the locality are not exceeded with respect to pH. In this experiment, since the disposal route for the water was infiltration into made ground containing large amounts of crushed concrete, this was not an issue and the pH was not measured.

Loading with used lubricating oil

Since completion of the construction, natural rainfall had been such that a small amount of water had been discharging from both outlet pipes from time to time. The water body within the pavement subbase had thus been primed. On the day of the first hydrocarbon application a very slight fall of rain had occurred during the morning but had stopped at the time of oil application. The pavement surfaces were wet but neither of the parking bays was discharging water. Five litres of used lubricating oil was poured nominally at the centre of each bay. An artificial rain event was applied, by means of a hosepipe and sprinkler head, to both pavements at a rate equivalent to 13 mm/hour for 1 hour (as used in the previous experiment (Newman *et al.* 2004a)). Both outlets started to discharge water after 11 minutes. Grab samples of 100 ml were collected at 15 minute intervals over 4 hours. The samples were analysed in the field on a Horiba model OCMA-310 analyser which had been calibrated against a 'heavy oil' standard provided by the manufacturer. This instrument is an automated version of the American Society for Testing and Materials solvent extraction/IR spectrometry method D 3921-85 (ASTM 1985). The manufacturer's calibration and operational instructions (Horiba 2001) were followed throughout. A further 13 mm artificial rain event was applied the following day and a series of samples were collected at approximately hourly intervals. Alongside the sampling and analysis effort the collection tank was checked for free product and none was observed. Monitoring continued without further addition of hydrocarbons until the 40th day after the lubricating oil application (days L1–L40). Apart from the first week an attempt was made to make sampling visits on a 1 day per week basis but it was not always possible to collect samples on the scheduled day because of lack of discharge. During that period flow rates from the pavements on all the days of sampling (other than when rainfall was applied artificially) were below 20 ml/min (equivalent to 0.10 mm/hour) except for day L7 when the flow rates were 188 ml/min (0.98 mm/hour) and 160 ml/min (0.83 mm/hour) and day L40 when the flow rates were 25 ml/min (0.13 mm/hour) and 57 ml/min (0.30 mm/hour) (for recycled aggregate and virgin aggregate pavements respectively). During the period of sampling the total depth of rain falling at the nearest weather station (CW0710 Salford) was 394 mm (21–100 mm per month). The monthly mean temperatures during that period ranged from 18.2–5.3 °C with an overall mean of 10.2 °C (maximum 1 °C; minimum 3.2 °C).

Loading with diesel

On day L40, 11 samples were taken at 15 minute intervals before 8.5 litres of diesel was added to each bay at the same positions as the lubricating oil had been added. No artificial rain was applied as the pavements, in response to the natural rainfall, were discharging as indicated above. Sampling was resumed for 120 minutes at approximately 15 minute intervals (this set of samples designated D1). Sampling was then continued the next day with four samples collected on each sampling day until 109 days after the first diesel application (designated days D2–D109). On day D109 two samples were collected before a further 8.5 litres of oil was added to each parking bay, followed by the collection of eight samples over a period of 4 hours. On this day the pavement surfaces were dry and the pavements were discharging, but at rates of less than 20 ml/min (0.10 mm/hour). Four samples per day were then collected for the next 3 days and sampling was discontinued after finally collecting four samples on day D118. The receiving quarantine tanks were observed regularly until the test beds were demolished for another experiment some 24 months after the start of the experiment. On day D118, the last day of sampling, the flow rates were 24 ml/min (0.10 mm/hour) and 46 ml/min (0.24 mm/hour) for the recycled and virgin pavements respectively, and on all other sampling dates from day D2–D118 the flow rates were less than 20 ml/min (0.10 mm/hour).

RESULTS AND DISCUSSION

Figures 3–5 show the results obtained in this study. Since the study produced discontinuous data the results are shown in the form of bar charts with columns shown only when a site visit was able to provide samples for analysis. It should not be implied that all days without a column shown are either days when the pavements were not discharging or, importantly, that the concentrations of oil were measured at zero.

Response to lubricating oil loading

Figure 3 shows the variation of concentrations of oil in the effluent from the two bays for the 2 working days from the start of the discharge from the parking bays following the addition of the lubricating oil. The majority of samples had concentrations well below the 5 mg/l limit for a class 1 interceptor (British Standards Institution 2002). Studies involving the artificial addition of large amounts of oil to real pervious pavement car parks are, for obvious reasons, very rare. It is possible therefore to compare the results obtained here with

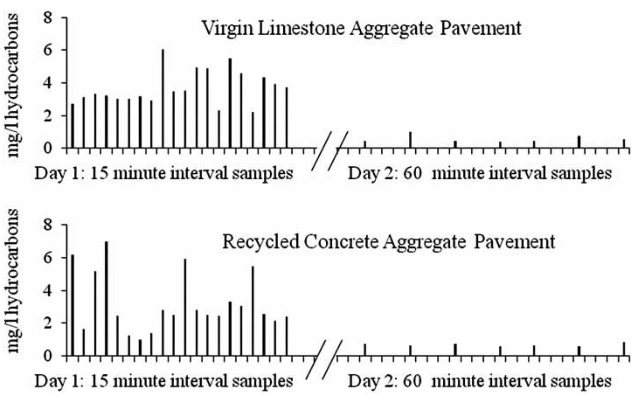

Figure 3 | Hydrocarbon concentrations in effluent. First 2 days after lubricating oil addition (nominal time series over 28 hours days L1 and L2).

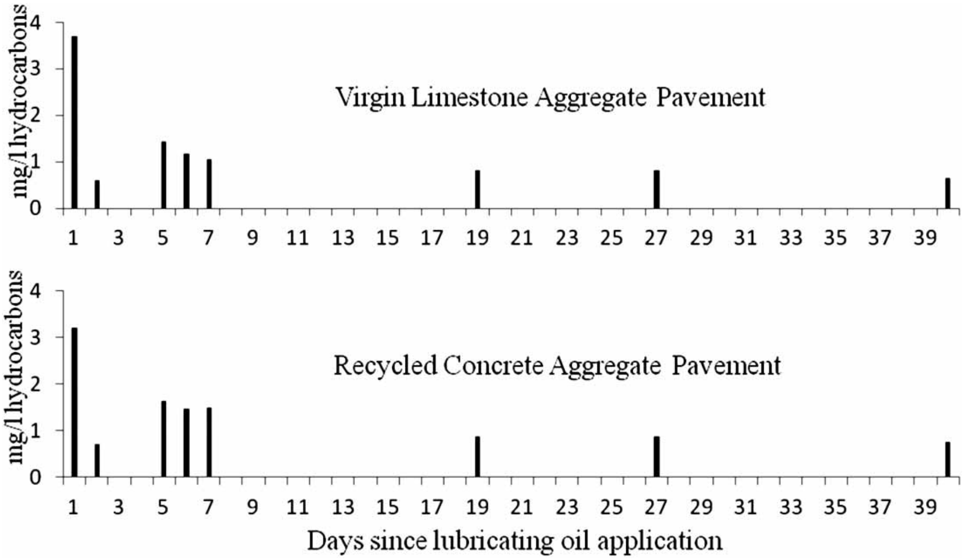

Figure 4 | Mean daily concentrations on: days L1–L40. Number of samples (n) = 20, day L1; n = 8, day L2; n = 4, days L5–L27; n = 11, day L40.

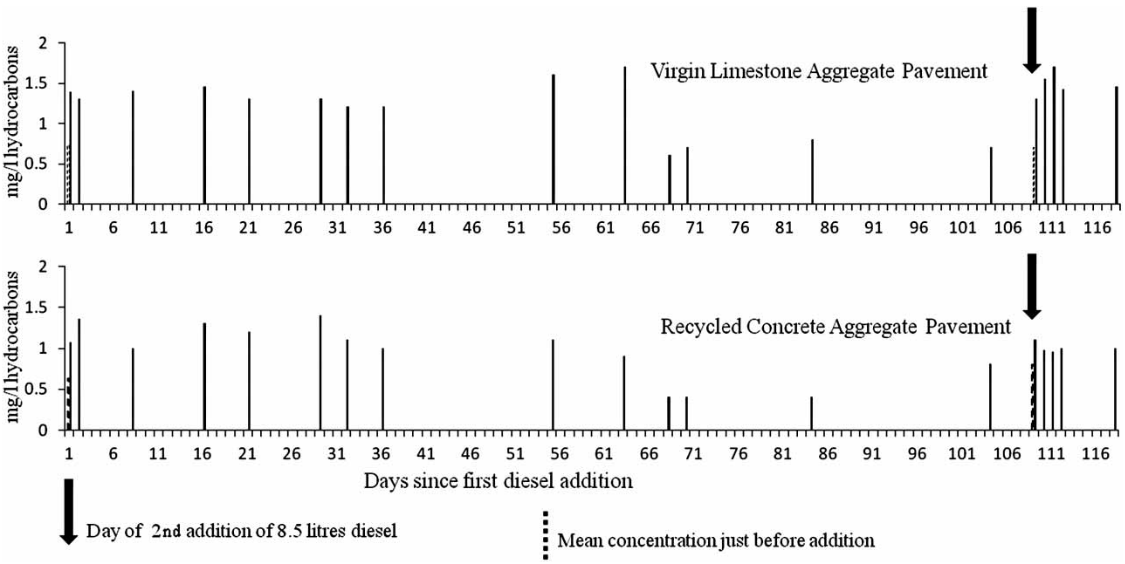

Figure 5 | Mean daily oil concentration on days from first diesel addition (days D1–D119).

a very limited selection of previous studies. This includes our previous work where the addition of a large tranche of lubricating oil was to a four-bay pervious car parking surface which was not provided with an integral gravity separation capability. In the current study the mean concentrations for the day of oil application were 3.2 mg/l (recycled) and 3.7 mg/l (virgin) which was, at first sight, poorer than for the earlier experiment. In that experiment the pavement was also loaded with 5 litres of oil and subject to the same simulated rainfall rate and gave first day concentrations of 0.5–2 mg/l. However the simulated rain event was applied across a four-bay parking surface (compared to a single bay in the current study), allowing escaping hydrocarbons to be diluted with water passing through a greater area of uncontaminated pavement. Taking into account this dilution the results are reasonably comparable.

The performance was also poorer than reported for the previous experiment based on a large-scale laboratory model of a plastic box based enhanced pavement model which used a baffle and weir arrangement to form the oil trap (Wilson *et al*. 2003).

This is possibly because the oil used in this indoor experiment was new oil. The presence of partially oxidised products in the used oil applied to the two parking bays may make both the kinetics and equilibrium parameters of oil dissolution less favourable than in our previous experiment.

Whenever not collecting samples, the effluent streams from the two parking bays under investigation were both directed into separate 1 m^3 quarantine tanks which allowed the observation for free product released and allowed an integrated sample to be obtained once the level in the tanks had reached the level of the drain tap. No free product was observed in either tank. The integrated samples from the tanks (collected on day L40) both had a concentration of 1.7 mg/l.

The day after the oil loading another 13 mm artificial rain event was applied and sampling was continued at approximately 1 hour intervals with the water directed into the quarantine tank between samples. It can be seen that between the first and second days the daily oil mean concentration fell to 0.7 mg/l (recycled) and 0.6 mg/l (virgin) respectively (maximum of 1.2 mg/l (virgin) and 0.9 mg/l (recycled)). At this time effectively 5 litres of free product was still present in the system. The second day performances of the enhanced pavements contrast sharply with that previously observed for the unenhanced pervious pavement system (Newman *et al.* 2004a), where on the day after oil application concentrations of over 8,000 mg/l (including copious amounts of free product) were observed. Clearly the retention mechanisms within the unenhanced system had been overwhelmed. Figure 4 shows the arithmetic mean of the (non-flow weighted) measurements made on those days when a subsequent site visit corresponded to days when the bays were discharging water.

It can be seen that the mean hydrocarbon concentration in both bays was around 1.5 mg/l by the end of the first week, falling to around 1 mg/l when measured at days L19, L27 and L40. The oil in the system would, by this time, be expected to be present in a number of different forms. Some would be in the form of a semi-continuous body of free product floating on the water body, but some would be smeared across a vertical section of aggregate by rise and fall of the water table in response to rain. It was also expected that some oil would be trapped on the upper geotextile either directly as it broke through into underlying subbase or, possibly, by being trapped in a secondary way as the rising water level lifts the free oil body to make contact with the polyolefin geotextile, known to be an effective oil sorbent. Given that so much free product is still present in the system the question arises as to why the measured hydrocarbon concentration falls. A number of potential reasons can be proposed. The most likely is that over time the concentrations of the most water-soluble (both in terms of absolute solubility and the rate at which equilibrium can be reached) components are depleted. Other possible mechanisms are the development of an oil-degrading biofilm in the system. Unfortunately, when the test bed was demolished no attempt was made to investigate this further and clearly there is a need for further work in this area.

Response to diesel loading

As indicated previously this part of the experiment involved loading both of the, already contaminated, parking bays with two 8.5 litre applications of diesel. In the 120 minutes after the first diesel addition the highest concentration in either test bed was 4.2 mg/l, the peak occurring at 45 minutes in the recycled aggregate bay. By 120 minutes the concentrations in effluent from the recycled aggregate bay was 1.0 mg/l and for the virgin limestone aggregate bay it was 1.2 mg/l. Figure 5 shows the daily mean concentrations recorded for the two test beds in the 118 days following the first diesel (days D1–D118). The mean value for all the measurements on the two pavements throughout this 118 day period was 1.2 mg/l. The maximum single measurement after day D1 was 2.6 mg/l.

No observations of free product were ever made in the quarantine tanks over the period of the experiment or indeed the period from the first oil addition to the destruction of the test beds some 2 years later. By the end of sampling, the two parking bays each contained around 22 litres of hydrocarbon product. If a 35% void ratio is assumed this would correspond to a hydrocarbon layer of around 5 mm thick. When the systems were finally dismantled the free product thickness, although difficult to measure accurately, was much less than this. This is not surprising. In Newman *et al.* (2004b) it was estimated that the blocks, laying course and geotextile retained 30–40% of the lubricating oil applied, with the remainder appearing as free product on the body of water within the plastic box storage layer. The systems under test here also had large surface areas of aggregate to be smeared over, and when the systems were dismantled it was clear that a significant amount of hydrocarbon had done so.

CONCLUSION

Whilst accepting the limitations of the intermittent sampling approach used in this study it is believed that this experiment has further illustrated the effectiveness of providing a near-surface gravity separator into a pervious pavement subbase, in this case on a much simplified system based on an aggregate subbase rather than the plastic box based system previously studied. Dissolved/dispersed hydrocarbons were present at easily measurable but acceptable concentrations, but the most significant observation was that, despite the addition of very large quantities of lubricating oil and diesel, free product hydrocarbon was never observed in the outflowing effluent or in the quarantine tanks used to retain the effluent prior to disposal. The total oil applied to each pavement could potentially produce an oil film covering a water surface of over 500 hectares. This has important consequences to the design of pervious pavements since a relatively minor adjustment to the outlet drainage system is able to provide confidence that, even in the event that a large oil spillage occurs, the immediate release of a large mass of hydrocarbons will be prevented and, even in the medium term, gradual release of dissolved and dispersed hydrocarbon would be acceptable, allowing time for a suitable remedial response

Clearly the volume of water in the permanently maintained water pool reduces the volume available for storage accordingly. If the same flow attenuation is required the depth of the subbase would need to be increased. The continual release of dissolved hydrocarbons from the system will be inevitable if the free product is not recovered. In this experimental system there was no provision for recovery of the spilled oil. In a plastic box based enhanced system it is easily possible to include provisions for an access chamber to be provided. The removal of the spilled oil, from an open tank supported by plastic pillars, would be much easier than for a stone based system where the aggregate provides a large surface over which residuals can be smeared, and any attempt to remediate the smeared oil from an aggregate based system would result in the need to treat or dispose of large volumes of contaminated aggregate. A disadvantage of this system, compared to ones in which spilled oil can be retained before it enters the subbase (Newman *et al.* 2013), is that the oil is in contact with a relatively large volume of water. The total mass of hydrocarbon dissolving into this volume of water before saturation would be great and thus first flush hydrocarbon concentrations would be expected to be higher. Further work in this area is warranted. In particular a repeat of this experiment over a longer sampling period and where resources are available for automated sampling would provide a clearer picture of the performance. Furthermore, full-scale field trials in areas of high potential for oil spillage would be of great help. However, ethical and regulatory considerations would make deliberate oil application to such a system impossible unless the system were provided with a further level of effective downstream oil interception.

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