8th International Conference on Concrete Block Paving, November 6-8, 2006 San Francisco, California USA

POLLUTION RETENTION AND BIODEGRADATION WITHIN PERMEABLE PAVEMENTS

A.P. Newman[1] S.J. Coupe[1]* and K. Robinson[2]
[1]Coventry University, Faculty of Engineering and Computing,
Priory Street, Coventry CV1 5FB, UK coopsy876@hotmail.com
[2]Formpave Limited, Tufthorn Avenue, Coleford, Gloucestershire, GL16 8PR, UK.
* Corresponding author

SUMMARY

Pervious paving systems (meant to mean permeable pavements within this context and used interchangeably) have been demonstrated to effectively and efficiently trap and degrade urban-derived pollutants such as hydrocarbons and metals. UK research by Formpave and Coventry University has demonstrated that 98.7 % of applied mineral oil is retained within the pavement structure over a test period of five years. Retained oils are subject to extensive biodegradation with around 45 % of that added to a permeable pavement system degraded within six months.

The key to the success of the paving system is the geotextile membrane layer located beneath the bedding layer. The physical and chemical properties of the geotextile reduce the velocity of water flow, immobilise the pollutants and provide an appropriate habitat for the growth of a microbial biofilm that degrades the oil. Pervious pavements have been installed all over the world and have been a significant contributor to the source control of pollution and to the drive for sustainable drainage systems (SUDS) in the UK.

1. INTRODUCTION

Traditionally, stormwater runoff from impermeable surfaces has been intercepted and discharged swiftly to sewer systems and watercourses. Rapid growth of urban and industrial areas has resulted in an associated increase in impermeable surfaces such as roofs, highways and paved surfaces placing an increased burden on existing drainage networks and urban watercourses. During periods of heavy rain, large volumes of runoff may exceed the capacity of sewer systems, resulting in risks of flooding to property and to human health. In addition, pollutants deposited on impermeable surfaces may be entrained by stormwater flow, concentrated within drainage systems, and discharged to aquatic ecosystems with little or no treatment. Urban stormwater can contain toxins, such as heavy metals, oil and other hydrocarbons and average levels of suspended solids may exceed that of untreated sewage. About 25 years ago the traditional means of drainage of land and property started to be recognised as having a number of environmentally damaging impacts. These impacts include catchment scale and regional scale impacts in addition to more immediately obvious local impacts on the drainage system. Flooding, erosion, pollution from poor quality stormwater discharges or combined sewer overflows, reduction of stream flows and water supply shortages are all considered as potential problems arising from the use of traditional drainage. Drainage designs intended to take into account these concerns are now known in the UK as sustainable urban drainage systems (SUDS). In the early years of SUDS development in the UK quantity aspects, and thus flood prevention, dominated design thinking until the more recent holistic approach started to evolve. SUDS achieve their improved performance, relative to traditional systems, by seeking to limit the discharge of stormwater from an area, both in flow rate and in volume, enhancing the water quality of both discharges to surface waters infiltrating water and incorporating devices which are, where appropriate, optimised to improve amenity. SUDS devices include a range of soft landscape type devices in addition to more engineered structures such as French drains, soakaways and, the subject of this paper, pervious pavements.

Correct scheduling of works ensures that the appropriate devices are in place before the potentially polluting activities begin and also to ensure that the SUDS devices themselves are not damaged by construction activities. This might also include the use of such features as temporary swales, detention basins and retention ponds for site sediment control and devices such as hydrocarbon-retaining temporary refuelling stands (Wilson *et al.* 2003) and in the case of pervious pavements this can be particularly important as hydraulic failure due to blockage is never found in such systems except where heavily loaded with silts due to bad management.

The greatest progress in SUDS in the UK has been made in Scotland where the quality, quantity and amenity aspects have all been given appropriate prominence by the Scottish Environmental Protection Agency (SEPA) since its formation in 1996 (Collins, 2004). Here a number of sites have used an integrated SUDS approach on areas in excess of several tens of hectares but in both England and Scotland hundreds of smaller sites have installed individual SUDS components, particularly permeable car parking surfaces and pedestrian areas. In the UK 400,000 m^2 of permeable paving blocks were sold by Formpave in 2006.

The pervious surfaces studied at Coventry has been almost exclusively based on non-porous concrete block surfaces in which the water is allowed to percolate through the surface via a block design which provides infiltration channels of one type or another. The most common type of block used has been the Aquaflow design a standard sized concrete block provided with an infiltration channel on one short end. The subbase on which these blocks have been laid (63-10 mm size grading) has invariably utilised a polypropylene geotextile between the load bearing/water storage layer (usually 50mm granite or similar) and the upper bedding layer (5 or 10mm granite or 10mm split pea gravel). This polyalkane geotextile plays an important role in both retention and biodegradation of hydrocarbons (Pratt et al. 2001). Because pervious pavements are commonly used in car parking applications the retention/biodegradation of hydrocarbons such as lubricating oils has been a major focus of our work, building on early work by Pratt (1996).

Typical values of run-off concentrations of waters from car parking surfaces are not easy to come by, not least because of the variety of sampling and analytical regimes which have been used. If we take an overview of the literature on the subject a concentration in the first flush of a storm might typically be around 30mg/l. The figures for car parking areas and other types of urban run off are probably not significantly different. For instance Perry and McIntyre (1986) reported run off concentration from the M1 near Luton at 30mg/l and in Seattle urban run off is reported between 0.2 and 16 mg/l total oil and grease with freeway run-off at between 10 and 60 mg/l.(Wakenham 1977)

Stenstrom *et al.* (1984) reported seven different storm events at a single car park with sample numbers per storm ranging from 6 to 13. What is remarkable about this set of results is the tremendous variability between storms with mean concentrations ranging from 8 to 31mg/l and within storms the typical coefficient of variability was around 30% and as high as 90% in one case.

As examples from Europe we can look at the report by United Nations Environment Programme (2000) which looked at urban run-off as a potential water resource and reported the concentrations of "oil products" in rainwater ranging from 2-24 mg/kg, snowmelt 35-72mg/kg and what it referred to as "street washwater" in the range 2-72 mg/kg. The figures reported from both USA and Eastern Europe are also largely in agreement with Mitchell *et al.* (2000) who give values for N Europe ranging from 10^{-1} to $10^{2.5}$ mg/l oil in a graphical plot which clearly showed a log-normal distribution of the data. In fact this data illustrates that values higher than 100mg/l are very rare.

In our laboratory a survey of the literature in the early 1990s led us to conclude, as a basis for our experimental work on porous pavements, that a concentration of about 1800 mg/l (applied as a combination of oil and rainfall) would represent about 100 times the loading of a typical car park (Bond 1999). This value is very much in line with the upper quartile values recommended by Mitchell *et al.* (2000) as values to be used for planning purposes.

This paper aims to present an abridged review of the work on retention and bioremediation of hydrocarbon pollutants carried out by the PPS Research Group at Coventry University starting with the small scale laboratory experiments in the mid 1990s, bringing the work up to date with preliminary results from an ongoing field based experiment.

2. LABORATORY BASED STUDIES- COMPARATIVE OIL RETENTION STUDIES

An early question which was addressed in our work was how well pervious pavements retain hydrocarbons compared to traditional car parking/highway surfaces. The aim here was to study PPS structures to find the oil breakthrough capacity and compare them with traditional parking surface materials (Newman *et al.* 1998). The pavement model used comprised proprietary concrete blocks bedded on clean pea gravel, with vertical drainage provided through gravel filled inlets between the blocks. A polypropylene/polyethylene geotextile (Exxon Terram 1000) separated the block bed from the underlying sub-base, comprising 400 mm depth of washed 20-50 mm granite. The entire structure rested on an additional geotextile underlay, supported by a stainless steel mesh. The structure was set up in steel/aluminium boxes having a plane area of 400mm x 400 mm and a height of 600 mm. Each box had an open bottom with a 300 mm deep pyramidal funnel for the collection of the effluent samples. At the funnel outlet, a tap was fixed, preventing unintentional effluent loss.

Two typical highway materials, asphalt and concrete, were chosen for investigation alongside the PPS. Eight identical aluminium trays were manufactured (310mm x 310 mm plan area, 50mm deep) from 1 mm thick aluminium sheet. On one side of each tray, a 310 mm wide effluent channel was fixed. This channel was used to collect the effluent from the trays and direct it to the collection bottles.

Mature asphalt blocks from a redundant area of footway, not previously exposed to oil were cut into rectangular pieces. The asphalt blocks, supported on a suitably thick layer of sharp sand were placed inside the trays as close as possible to their front sides. The slight gaps between the asphalt structures and the sides of the aluminium trays were filled with sharp sand and finally sealed with multi-purpose silicone sealant. Four sets of this apparatus were constructed. For the concrete experiments, grade C40 concrete was cast directly into the aluminium trays. For a nine-week period, three rainfall events per week were simulated (using a device previously described by Bond *et al.* (1999)) on each structure. The rainfall intensity was set at 13 mm/h for duration of approximately 28 minutes, applying an amount of

263.5 ml distilled water to each pavement per rain event. Oil was applied (simulating crank-case leakage) to each structure (except the controls, one per structure type) by means of calibrated oil drippers described previously (Newman *et al.* 1998) placed randomly. The amount of oil added per event was increased in a stepwise manner (starting at 0.8ml per oil application and increasing to 20ml) over the experiment in an attempt to try to reach saturation potential of the PPS in a reasonable period. Oil was applied on the morning prior to each rain event. The data is also presented as a table giving the total proportion of oil and grease retained for each structure type over the experimental period. The results of this retention experiment are shown graphically in figure 1.

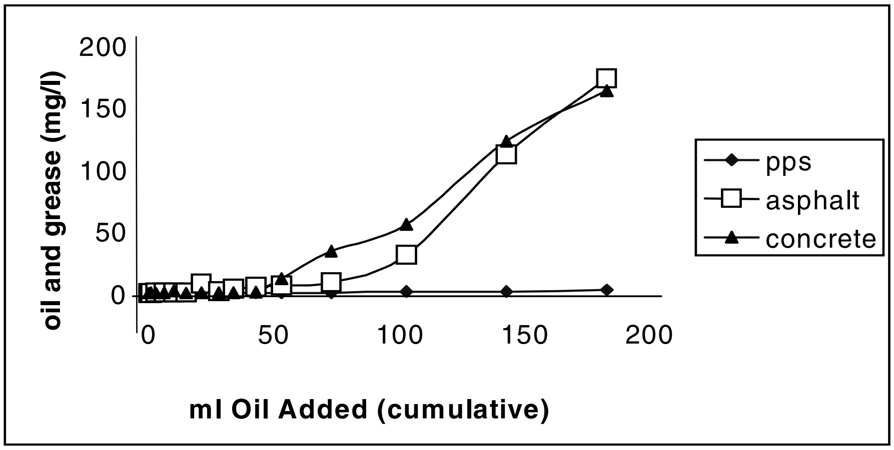

Figure 1. Graph of cumulative volume of oil added against concentration of oil released for PPS, asphalt and concrete (means of three replicates) Horizontal graph axis set at y = –5mg/l for clarity.

It is clear that the PPS is considerably more retentive of the oil than the traditional structures. A concentration of 0.25mg/l oil and grease in the effluent (our arbitrary "breakthrough" concentration) occurs in the PPS model at about 100ml of added oil. This corresponds to an oil application of roughly 500ml per m^2. At the point where 100ml of oil had been added to the traditional structures the concrete and asphalt structure effluents were approximately 25mg/l and 50mg/l respectively. At the end of the experiment after the addition of 183ml of oil the concentration in the effluents from the asphalt and concrete were in the region of 150mg/l oil and grease with free oil clearly present in the samples. At this point the concentration in the PPS effluent was less than 1mg/l. Overall during this experiment the PPS system retained 97% of the oil compared to 50% for the asphalt and 70% for the concrete.

This experiment was designed to minimise the effects of biodegradation in the PPS structures. In an experiment started by Bond *et al.* (1999) and completed by Coupe (2001) in which biodegradation was encouraged by adding inorganic nutrients an appreciation of the long term capabilities of the system could be obtained. A representative section of the pavement was constructed as described above (except that the depth of sub base was 600mm and the plan area was 600mm x 600mm) in a steel/glass box.

Lubricating oil additions of approximately 3.3g per week were applied except during periods of holidays and staff changeover. The upper line in figure 2 shows the actual rates at which oil was applied during the period of the experiment. Rainfall events at 1.6mm/hr were applied on average once every 3.5 days (approximating to the mean for London (Wallén 1970) except during deliberate drought periods. All effluents were analysed for oil and grease and the results are presented as a plot of cumulative mass of oil and grease added and cumulative mass of oil and grease detected in effluent against time, over the whole 1150 days of the experiment. The fact that the lower line is hardly discernable from the baseline is indicative of the high capability of retention.

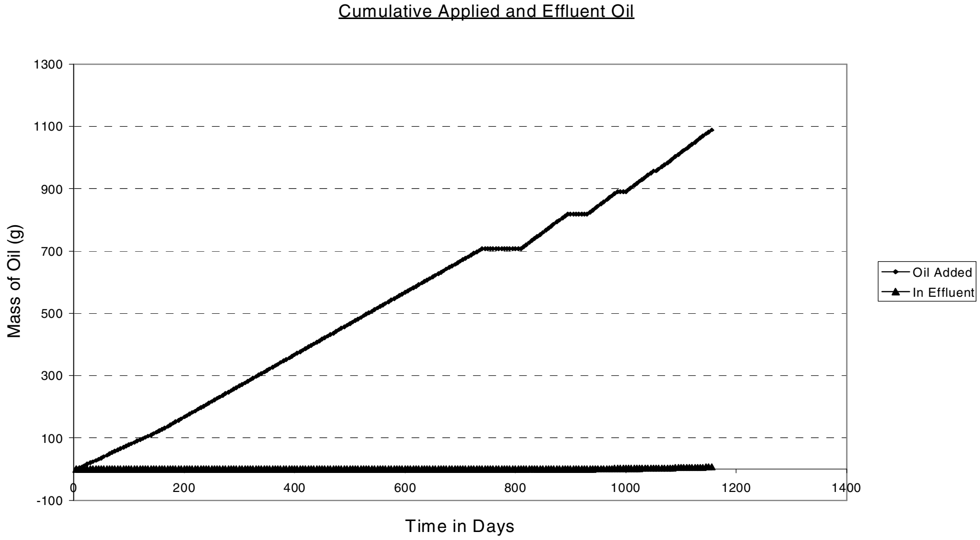

Figure 2. Graphs of cumulative mass of oil added (upper line) and released in effluent (lower line) for first 1150 days of experiment.

Whilst working with the Coventry research group Bond also carried out work to identify where oil was retained in the PPS (Bond 1999) and the rates at which biodegradation takes place when supplied with suitable inorganic nutrients. Details of these experiments are presented elsewhere but at this point it is appropriate to consider the summary of his results presented in figure 3. The two most significant items of note are the fact that around 31% of the added oil was degraded in 78 days and that on breaking down the structure at the end of the experiment 49 % of the oil added was found on the geotextile. Given that Bond was also able to demonstrate that the geotextile was the main region of biodegradation (Bond 1999) it would seem logical that around 70-80% of the added oil is intercepted by the geotextile. Another paper at this conference will deal with the mechanism of oil retention by the geotextile and the microbiological role that it plays (Coupe *et al.* 2006).

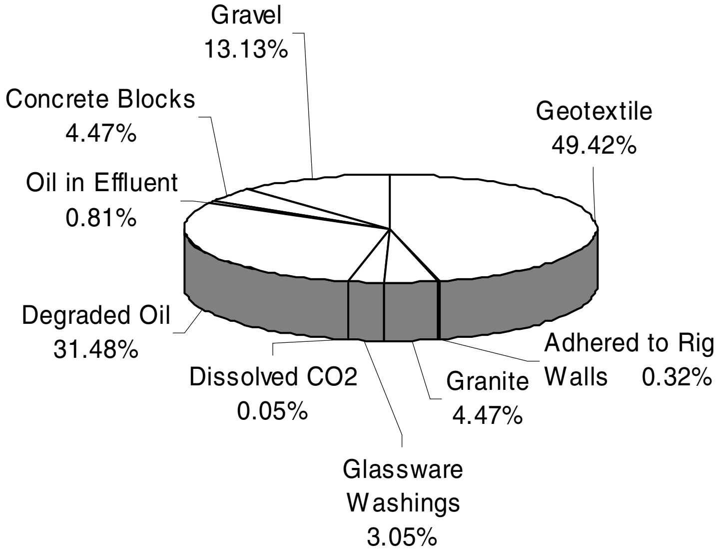

Figure 3. Pie diagram showing distribution of remaining oil on a test rig following a 78 day experiment.

3. FIELD BASED EXPERIMENT

Whilst field studies of hydrocarbon retention in PPS based car parking surfaces using the accidental drips of oils from parked cars in normal use (e.g. Brattebo and Booth 2003) studies using accelerated pollution levels by adding additional oil have (for obvious reasons) been rare. Puehmeier *et al.* (2004) carried out a large scale outdoor experiment involving the addition of oil throughout the surface of a car park. This experiment made use of a large-scale outdoor car-parking model, originally constructed by Coupe (2001). The model was used as part of the Coventry University staff car park for periods of 16 months with periodic grab sampling of natural rain events. During this period the measured concentration of oil was always below the limit of detection of the Horiba analyser used. The experiment reported by Puehmeier was carried out when this experimental car park was due to be demolished due to building works. An additional oil loading was made to the model at rate of 150ml used engine oil per m^2 which was applied by injection with a 10ml syringe into the gaps between the blocks haphazardly within a series of contiguous quadrats over the entire parking surface using a 10ml syringe to inject between the blocks. This resulted in 1012 injections being made into the six bay car park plot. Following this addition of oil grab samples were collected from the first significant natural rain event which followed and the samples were analysed using the Horiba® analyser. Unfortunately there was no subsequent significant rainfall between this rain event and the destruction of the models due to building works. In the first rain event following the additional oil application there was no oil and grease detectable for approximately 1.5 hours after the rain has started. Throughout the whole sampling period was no free product visually observable.

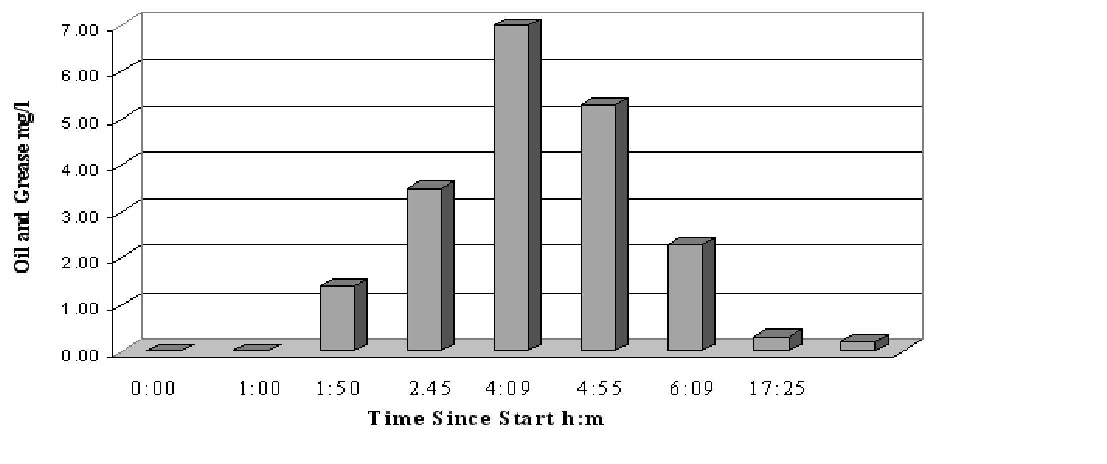

Figure 4. Graph of Oil and Grease content in the Rig effluent. Adapted from Puehmeier *et al.* 2004

The model showed a maximum 7 mg/l. The results showed a remarkable performance to deal with a considerable loading of oil.

4. SELECTION OF APPROPRIATE GEOTEXTILES

In the work described above heat bonded, non-woven geotextiles had been used. It was not proven that this was optimum and indeed it was probably a fortuitous choice at the time the experiments stated. Woven geotextiles are cheaper than non-wovens of the same strength but a theory had arisen from our previous experience that the retention of hydrocarbons was, in part, due to the higher water breakthrough head exhibited by the non-wovens. The proposal was that in a rainstorm water would pool on the geotextile forming a temporary gravity separator for free phase oil washed down from above. At the end of the storm water would penetrate the geotextile until the depth of water was less than the breakthrough head. The water would then evaporate from the upper layers and when the oil encounters the geotextile it will have virtually zero velocity and insufficient energy to penetrate the geotextile. The hydrocarbon would then have the opportunity to interact chemically and physically with the polyalkane geotextile. In subsequent rain events hydrocarbons not strongly attached to the geotextile will again float on the water pool. The process is also likely to encourage the spread of hydrocarbons across the geotextile surface encouraging the formation of oil degrading biofilm over the geotextile surface. This experiment compared a traditional non-woven geotextile with a thicker, felt-like, non-woven and a typical woven type. Figure 5 presents a conceptual model of the processes taking place.

This experiment compared a traditional non-woven geotextile with a thicker, felt-like, non-woven and a typical woven type. An experimental set up involving thirty, small scale models based on plastic plant pots was constructed. Ten of each of three types of geotextile were placed into the model, with and without simulated silt. Ten models were equipped with typical non-woven geotextile, ten with a thicker geo-textile felt (both non-woven) and ten with a woven geotextile.

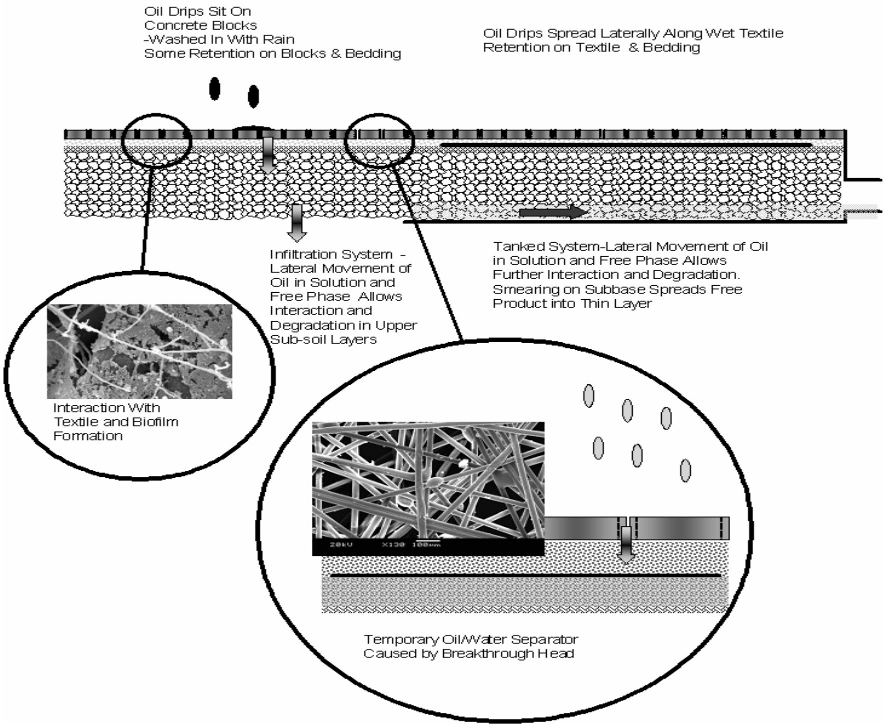

Figure 5. Conceptual model diagram of the processes of oil retention occurring in the pervious pavement.

In each group, 5 models were produced using the traditional construction system (geotextile separating 50 mm granite subbase from 10 mm pea gravel bedding layer) previously used in the pervious pavement research at Coventry University (Pratt *et al.*, 1999), and 5 were used to study the effects of siltation by incorporating a 5 mm layer of simulated silt just above the geotextile. The models used were 110 mm in height and with a diameter of 125 mm. After 4 ml of oil was added to each model a simulated rain event (130 ml of simulated rain were applied to each model at a simulated rainfall rate of 24 mm/hour) was applied. The rainfall simulator used in the experiment for applying "rain" onto each of the models has been extensively described elsewhere (Pratt *et al..,* 1996. After the simulated rain, another 4 ml of oil was added again within a 2-day interval. Water samples were collected at each rain event. This was used to simulate the contamination by oil in both wet and dry conditions. For each cycle, 8 ml oil was added to each model.

The experiment was carried out in three cycles, which took place over a three week period. Figure 6 represents the relative performance of the two non-woven and one woven geotextiles in model pervious pavement systems.

It can be seen clearly that the woven geotextile gives a poorer performance than the non-wovens and that, for this product, the presence of silt makes a significant difference to the retention of oil. Whether this is due to sorption on the trapped particulates or because the particulates increase the breakthrough head is unclear. It is also important to note that the choice of geotextile has important microbiological consequences.

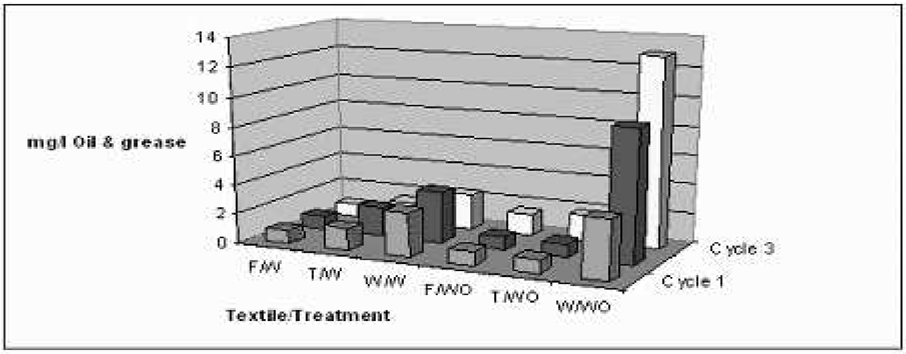

Figure 6. Concentration of Oil and Grease in effluents from models with various geotextiles. T and F are non-woven, W is a woven geotextile. W and WO represent with and without added artificial silt respectively.

Whilst much of the work on geotextiles has been carried out using Terram 1000 geotextile a new product, which contains certain additives in addition to the polyethylene/polypropylene contained in the standard product, became the product specified for use in conjunction with Formpave Aquaflow blocks. The microbiological qualities of this product needed to be checked to establish that biofilm would rapidly form under appropriate conditions. Figure 7 shows two scanning electron microscope images of Inbitex at two different magnifications following 7 days incubation in an oil rich medium inoculated with organisms extracted from a long term PPS model structure. Figure 7 (b) is at high magnification and the wide range of bacterial types can be clearly seen. Figure 7 A illustrates the fact that under the correct conditions biofilm can bridge between the polyalkane fibres.

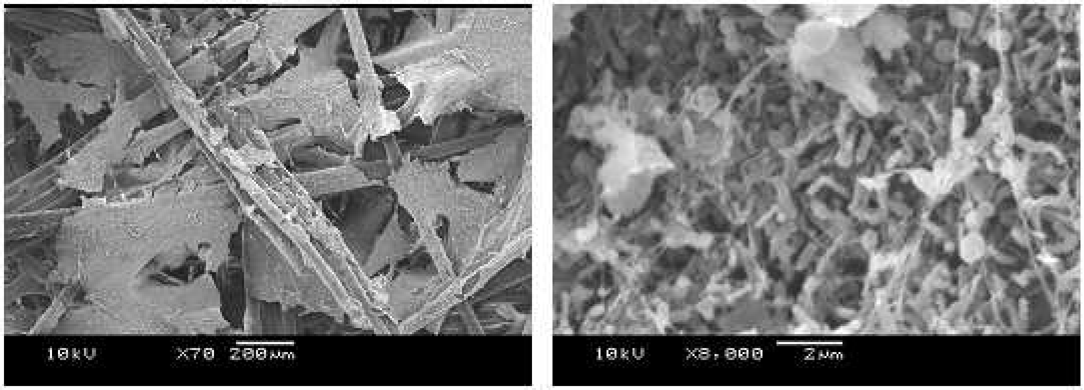

Figure 7. Images of Inbitex geotextile after 7 days incubation.

(a) **(b)**

5. CONCLUSIONS

The use of pervious pavements in a pollution control role is now well established and it is established that the design based on concrete block paving over a stone subbase, separated from a bedding layer formed with 5-10mm bedding layer by a polyalkane geotextile has remarkable hydrocarbon retaining capabilities and is capable of supporting rapid biodegradation of hydrocarbons under suitable conditions.

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