Irrigation using Permeable Paving as the Source of Water: Effects of Recycled Water on the Soil; Plant Growth and Development

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ABSTRACT

This paper reports experiments where water from geotextile incorporated pervious pavement system models on which 24ml per m^2 of hydrocarbon was applied as a pollutant; and a single dose of 17g of NPK slow release nutrients (applied to encourage biodegradation) was administered to the surface was used to irrigate tomato plants (Lycopersicon esculentum (fantasio hybrid)) and rye grass (Lolium Perenne) for 10 weeks. The growth, development and heavy metal content of the organs of these plants were compared to that of plants from untreated rigs and with plants treated with de-ionized water (DI) as well as the soil pH and Electrical Conductivity (EC).

The comparative performance of the plants indicated that the water from the treated rigs supported plant growth more than the water from the untreated test rigs and DI. Heavy metal analysis of the plants organs indicated that the metals were at normal levels and below toxicity levels for plants and livestock. Soil structure tests showed that there was no salinisation or serious soil structure issues. Heavy metal analysis of soil also indicated that the metals were within normal range and below toxicity levels.

These results further demonstrate the water recycling capability of the PPS for irrigation purposes and the need to harness this potential.

KEYWORDS
Water re-use, irrigation, pervious pavements, hydrocarbons, eutrophication.

1. INTRODUCTION

Urban stormwater can contain toxins, such as heavy metals, oil and other hydrocarbons and excess levels of suspended solids. Fortunately the traditional means of drainage of land and property, for some time, been recognised as having a number of environmentally damaging impacts (e.g. Stenstrom et al., 1984) and drainage designs intended to take into account these concerns (now known in the UK as sustainable urban drainage systems (SUDS)) are becoming increasingly common, including, the subject of this paper, the pervious pavement system (PPS) which have found particular application as permeable car parking surfaces (e.g. Brattebo and Booth, 2003).

The pervious pavement system (PPS) has the potential to offer additional benefit in the areas of rainwater harvesting and storage. Recycling rainwater using the PPS would reduce over dependence on high quality mains water for low grade uses such as flushing of toilet, car washing, irrigation, e.t.c.

The pervious surfaces studied by the Coventry PPS group have 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 structure on which these blocks have been laid has invariably utilised a geotextile between the load bearing/water storage layer (which could be either a stone subbase or a plastic, void forming subbase replacement.) and the upper bedding layer (5 or 10mm granite, limestone or 10mm split pea gravel). This geotextile plays an important role in both retention and biodegradation of hydrocarbons (Bond, 1999) and although the oil retaining performance under heavy loading has been shown to be limited (Newman et al 2004; Puehmeier, 2008) under loadings representing day to day drip additions from car parks they have been shown to develop effective biodegrading biofilms (Newman et al 2002; Coupe et al 2003) and to retain a high proportion of added oil (Bond, 1999). 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 the early work by Pratt et al (1989).

Pervious pavement systems (PPSs) have been recognized as possessing the capability to be used as a stormwater harvesting and storage device. Whilst use for toilet flushing etc. is one avenue for the collected product in countries with intermittent and unpredictable rainfall the use for irrigation both in food production and in landscaping is a use which would seem highly attractive. Most of the warmer and drier countries are, quite naturally, important destinations for tourists from more temperate countries. Such tourists demand from the hotels and tourist facilities the quality of paved areas and parking surfaces found in their home countries and a standard of soft landscaping which is often incompatible with the rainfall regime in the area. This leads to requirements for irrigation with scarce water resources sometimes in countries where public access to safe water supplies cannot be assumed. Pressures on water for irrigation of non-agricultural areas is also growing as a result of an increasing trend for overseas holiday homes and retirement to the sun with a tendency to maintain links with home by growing non-native plants which have high water demands. This is often accompanied by the desire for each property to be provided with a driveway to park a car. Thus there is increased runoff of the stormwater and at the same time an apparent overuse of potable water for both domestic and hospitality based irrigation.

The experiment was originally designed to compare performance of plants using irrigation water derived from oil degrading models representing a proprietary plastic box water storage/sub base layer and stone-based sub layers used in more traditional pervious pavements. It was proposed that the two systems might show different performances due to differences in hydrocarbon (and hydrocarbon degradation product) contamination in the irrigation water and in the utilisation or sorption of the slow release nutrients added to the pavements to encourage biodegradation. The controls used in these experiments represented pedestrian paved areas not subjected to oil contamination and thus with no requirement for inorganic nutrient application. However, as will be seen from the results the differences between the two types of sub-base were minimal compared to the differences between the treated systems and both the controls and DI irrigated plants.

Successful irrigation projects involve not only the supplying of irrigation water to the land, but also the control of the salinity and alkali of the soil. If the amount of water applied to the soil is not in excess of the amount needed by plants, there will be no downward percolation below the root zone, and mineral matter will accumulate at that level. The characteristics of an irrigation water that seem to be most important in determining its suitability for irrigation include the total concentration of soluble salts, the relative proportion of sodium to other cations (usually expressed as the sodium absorption ratio) and the concentration of boron or other elements that may be toxic. (Ashraf & Harris, 2004; Rohsler & Wright, 1984) Some work has been done on studying direct application of free phase oil to growing plants (e.g. Barrett 2005) where significant harm had been detected at relatively low dosing but the potential effects the use of water stored in oiled PPS systems on seed germination, plant growth and development on water from such systems was not clear. This is particularly the case when, for purposes of enhancing biodegradation of hydrocarbon pollutants, the surfaces are supplied with slow release fertilizers since irrigation with fertilizer laden waters in which the balance of nutrients has been disturbed by selective removal by an oil degrading biofilm or sorption onto pavement materials seems not to have been studied.

2. MATERIALS AND METHODS

The experimental pavement models were built into welded HDPE containers equipped with a siphon device fitted into a void space created by a small section cut from a Permavoid plastic unit to allow withdrawal of irrigation water by siphon from the base of the models. Care was taken to ensure that the models were never fully emptied and thus any free product would not have been withdrawn as part of the irrigation waters. Thus any negative effects would be limited to dissolved contaminants. The cross sections of the models are illustrated in Figure 1. The depth of the stone sub-bases was 150mm, equal to the depth of the Permavoid plastic Units. A 50mm bedding of 10mm pea gravel was used to support the layer of Formpave Aquaflow block paving. Simulated rainfall intensities of 7.4mm/hr over 1 hour were applied at 3 events per week. A weekly dose of 6.23ml of lubricating oil was added to the series of 710mm x 360mm model permeable pavement structure. A single dose of 17g of slow release NPK granules (Osmocote) was administered to the surface of the pavement systems and brushed into the infiltration slots. Throughout the experiment the systems were maintained in the dark as much as possible to discourage algal growth in the siphon arrangement.

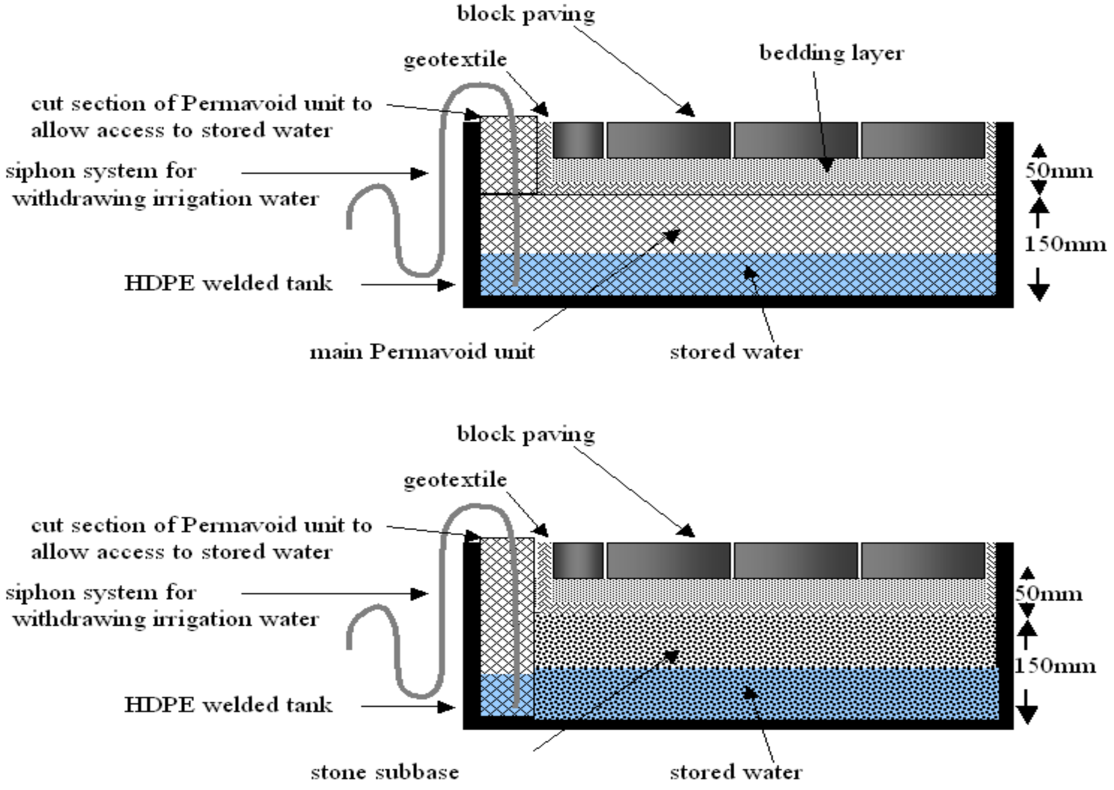

Figure 1 Schematics of the rig model types: Top-Permavoid Bottom-Stone Subbase

2.1 Plant Growth Experiments

Two plant types were selected for the greenhouse experiments representing both landscaping (rye grass) and horticultural (tomato) applications of the irrigation water.

2.1.1 Tomato Experiments

A total of 36 plastic plant pots (120mm high 14mm diameter) were filled with 200g of John Innes potting compost and each was planted with two tomato seeds (Lycopersicon esculentum (fantasio hybrid). 3 pots were assigned to each of the models and 4 pots were designated for watering with DI water.

The watering of the pots, using a watering can, was carried out 3 times per week. 100% germination was achieved and after 1 month the weakest seedling in each pot was removed. As indicated above, each model had 3 replicates assigned to it and these (and the DI water control pots) were arranged within an unheated greenhouse using a randomised block design for the plants irrigated with oiled rig water and the appropriate controls with DI-irrigated samples dealt with separately as an additional row. The plants were inspected daily except for most Sundays with the first flowering date and first detectable setting of fruit being recorded for each plant. Where necessary, bamboo canes were used to support the growing plants. After 70 days, when the first plants had reached a height of around 1m, the above-soil parts of the plants were harvested and the wet and dry weights of the stems leaves and fruit were separately determined.

2.1.2 Rye Grass Experiment

The rye grass experiment was again carried out using 3 pots per model and 4 pots for DI watering (identical to tomato experiment). A total of 36 pots were sown with 0.5g of rye grass (Lolium perenne) seed into the same compost as was used in the tomato experiment. An identical randomised block design to the tomato experiment was adopted for the rye grass. The same watering regime was used as in the tomato experiment. In this experiment the rye grass was harvested at soil level at 55 days and at 93 days. Wet and dry weights of the harvested grass were determined.

2.2 Chemical Analysis of Irrigation Waters

Water samples were analysed by ICP-OES for sodium, calcium and magnesium and the electrical conductivity and pH were determined on a weekly basis. From the cation data the sodium absorption ratio (Rohsler&Wright, 1984) was determined according to the formula:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\dfrac{\mathrm{Ca}^{++} + \mathrm{Mg}^{++}}{2}}} \qquad [1]$$

2.3 Chemical Analysis of Plant Organs

The harvested plant organs were dried in a forced-air oven at 80^{o}C for 3 days after which they were homogenized according to irrigation water treatments and digested in 70% analytical grade HNO_3 and H_2O_2 (supplied by Fisher Scientific, UK) in the ration of 3:2 using wet dissolution method.

3. RESULTS AND DISCUSSION

The basic quantitative results obtained from the two experiments are presented in Tables 2 and 3. It is clear from this table that there is little difference in performance between the plants watered with water from the two oiled sub-base type rigs. There is however considerable difference between the plants irrigated by oiled and control rigs and the oiled rigs and the DI water irrigated plants. These differences were all found to be significant at the 5% level. This is almost certainly due to the excess nutrients released from the oiled rigs enhancing the growth of both sets of plants. Clearly any inhibition caused by the presence of hydrocarbons in the water was more than made up for by the addition of the nutrients.

It must be remembered that this experiment was originally conceived as one to compare the two rig types and the tremendous difference in performance of plants irrigated with water from the oiled/fertilised rigs compared to the untreated controls was unexpected since earlier work by Barrett (2005) had indicated that the hydrocarbons would be expected to inhibit the plants and work by Bond (1999) indicated that the release of inorganic nutrients from the rigs would be minimal other than just after first application of the fertiliser. This leads us to consider that whilst the waters might be suitable for release via infiltration where attenuation on soil strata and dilution would be operating (and the effects would be little different from using the fertilizer in horticultural applications directly to soil) the release of effluent from pavements fertilised to give enhanced rates of biodegradation into a watercourse would be likely to cause eutrophication. This illustrates perhaps that except where the released nutrients are to be recycled or where the effluent from pervious pavements is to be used for such applications as toilet flushing the use of normal slow release fertilizers should not be encouraged in systems where the stormwater is collected in a sub surface tank for release to the surface water network of a separate drainage system. In such circumstances two approaches would seem to offer a solution. The first of these is the very slow release system reported by Spicer et al (2006) but as yet this system is not available commercially. The second might be to use a system capable of holding greater amounts of oil before saturation. Work within our group has shown (Puehmeier 2007) that even without enhancing the biofilm with an outside supply of fertilizer microbial activity (as measured by ATP determinations) is still present. Thus perhaps the key would be to hold the oil in the system long enough for natural attenuation process to take place.

Table 1 - Growth Parameters - Tomato Experiment

		Source of Irrigation Water			
	DI	Control		Treated	
Parameter	Water	Stone	Plastic	Stone	Plastic
Mean Height After 10 Weeks. m	0.85	0.82	0.92	1.01	1.12
Max. Height After 10 Weeks. m	0.74	0.80	0.80	0.81	0.87
Leaf Biomass - Wet Wt .(Mean) g	7.4	14.7	13.6	27.3	19.3
Stem Biomass - Wet Wt. (Mean) g	7.8	17.3	16.4	22.5	23.3
Fruit Biomass - Wet Wt (Mean) g	0.0	0.0	5.3	26.2	33.6
Mean Non-Root. Biomass - Wet g	15.2	32.0	33.3	76.0	76.2
Leaf Biomass - Dry Wt. (Mean) g	2.1	3.0	3.7	4.3	3.0
Stem Biomass - Dry Wt. (Mean) g	2.5	3.5	4.3	4.2	3.6
Fruit Biomass - Dry Wt. (Mean) g	0.0	0.0	0.5	1.9	2.4
Mean Non-Root. Biomass - Dry g	4.6	6.5	8.5	10.4	9.0
First Flowering Days from Sowing	51	55	49	48	51
First Fruit Set Days from Sowing	NA	NA	68	60	61

Table 2 - Growth Parameters - Rye Grass Experiment

		Source of Irrigation Water			
	DI	Control		Treated	
Parameter	Water	Plastic	Stone	Plastic	Stone
Wet Weight 1st Harvest g/pot.	4.32	8.92	8.75	11.18	11.23
Wet Weight 2nd Harvest g/pot.	2.53	3.71	4.63	11.57	8.52
Dry Weight 1st Harvest g/pot.	0.79	1.61	1.33	1.98	1.85
Dry Weight 2nd Harvest g/pot.	0.50	0.85	0.90	2.02	1.62

3.1 Chemical Analysis of Irrigation Waters

The results for pH, electrical conductivity and SAR are presented in figures 2, 3 and 4 respectively. For plant growth the range of tolerable pH in irrigation waters for plant growth is between 6.5 and 8.5 although this depends on the species being grown.

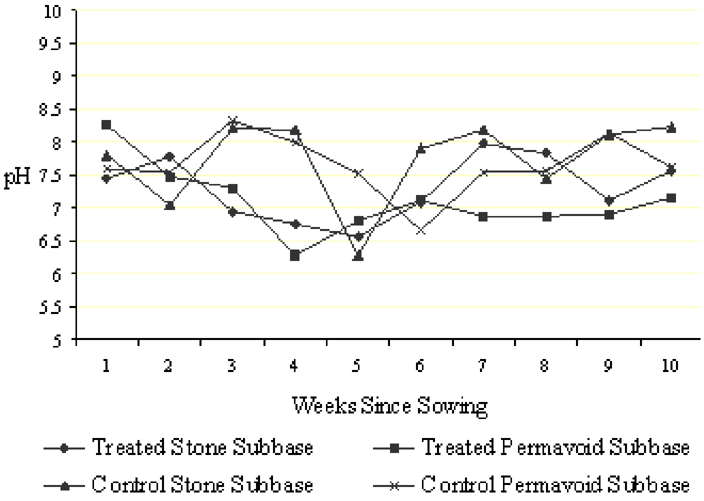

Figure 2 Weekly measurements of pH in irrigation waters (median)

Under the conditions of the experiments reported here the pH is not a limiting factor but for certain plants pH adjustment could be required. When electrical conductivity starts to exceed around 950µS/cm the benefits of the increase in nutrients starts to be counteracted by the osmotic harm caused by the dissolved salts in very sensitive crops with the maximum limit is around 12000 µS/cm (deHayr and Gordon 2006). Again it can be seen that electrical conductivity should not limit the use of the stored pavement water for irrigation even when salts are supplied as fertiliser nutrients. Indeed there is leeway to allow for significant evaporation during storage before the harmful dissolved salt concentrations are exceeded. Sodium absorption ratio is important in climates where there is likely to be significant evaporation of irrigation water. The accepted limit for SAR is around 12-15 (Munshower 1994) and thus the pavement water should not, at first sight, offer a problem. However the ratio of SAR and Electrical conductivity is also important for certain soil types and according to deHayr and Gordon (2006) the ratios obtained here are such that one might need to be cautious with certain soil types or, if in doubt, add supplementary calcium or magnesium salts before irrigation. If pH reduction is also required this could be conveniently achieved by addition of gypsum. A number of other chemical parameters have been measured but space does not allow inclusion in this paper. However on a note of caution it appropriate to report that the fertiliser balance aspects of this use of pavement water is far from simple and further work is required before the system could be said to be optimised. As an example it was found that after the experiment there was found to be a depletion of iron in the tomato growing medium following the experiment. It remains to be found whether the cause of this was uptake by plants or selective leaching.

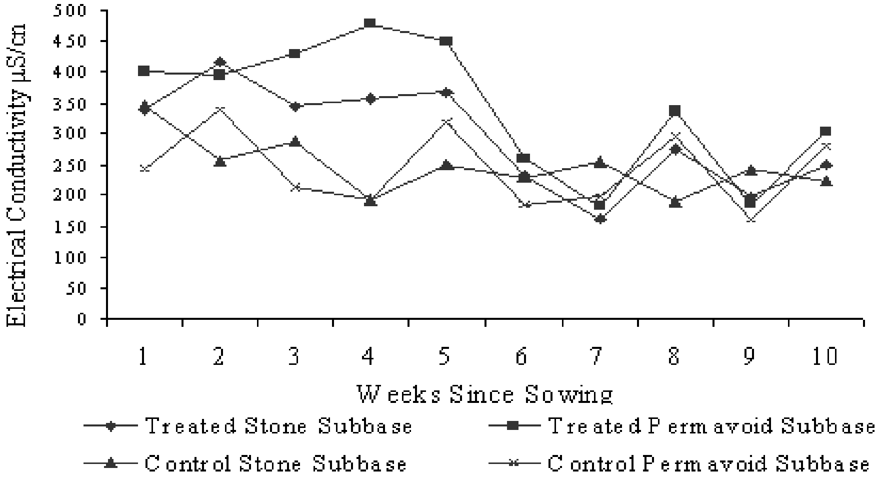

Figure 3 Weekly measurements of electrical conductivity in irrigation water (mean)

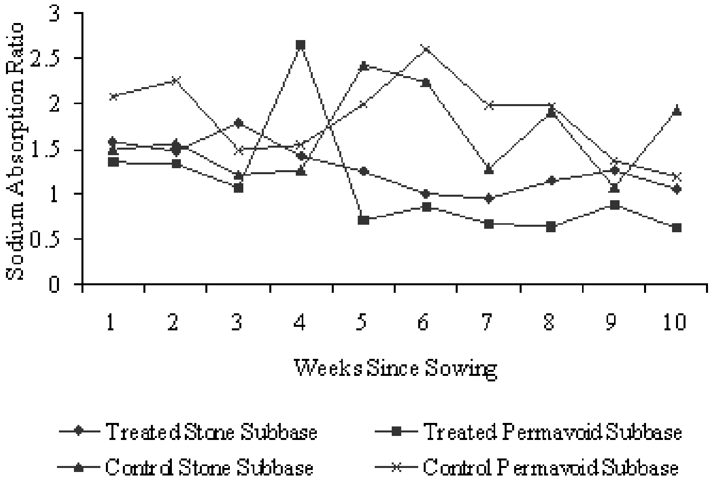

Figure 4 Weekly measurement of sodium absorption ratio in irrigation waters (mean)

3.2 Chemical Analysis of Plant Organs – Tomato

A relatively higher concentration of 20.1mg/kg of Zn was also observed in the stem of tomato plants irrigated with DI water and the lowest level of 9.2mg/kg was observed in the stem of tomato plants treated with water from control plastic test rig as shown in figure 5.

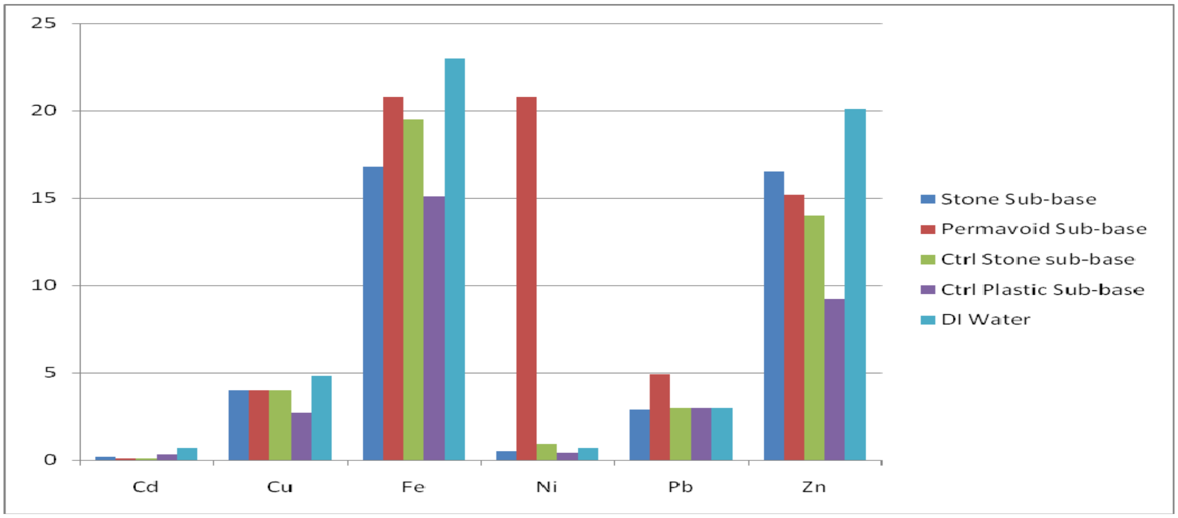

Figure 5 - Metals in Tomato Stem

However, there was no significant difference (ANOVA: $p>0.05$) between the levels of Zn in the stem of tomato plants that were treated with water from the Stone, plastic and control Stone sub-base test rigs with Zn concentration range of between 14 – 16.5mg/kg.

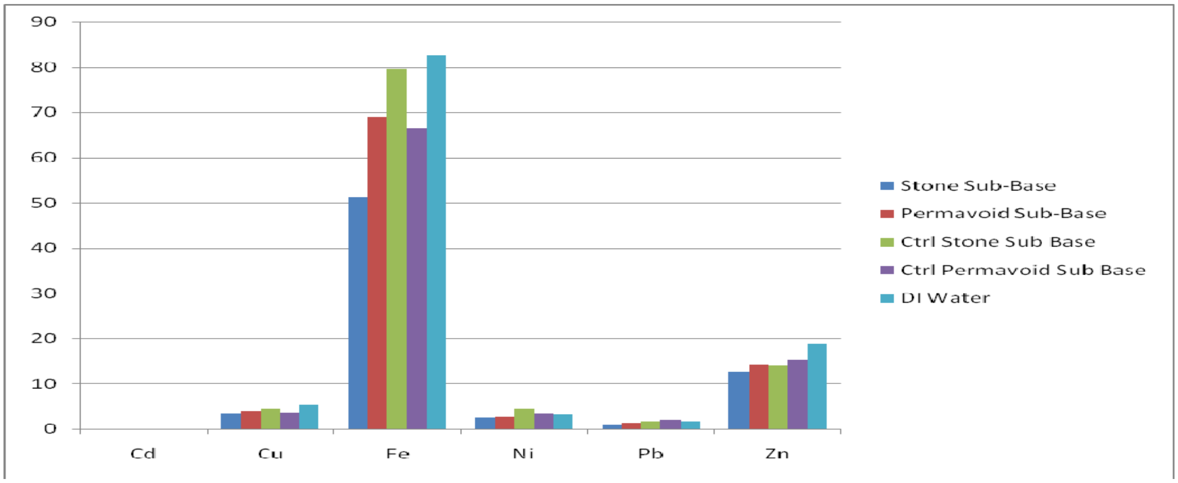

Figure 6 - Metals in Tomato Leaves

Similarly, there was no significant difference (ANOVA: $p > 0.05$) between the levels of Cu, Ni, Pb, and Zn in all the leaf samples analyzed including those irrigated with DI water as shown in figure 6. The level of Cu, Ni, Pb and Zn in all the tomato leaves was within the normal range as shown in table 3.

Table 3 - Normal and Phytotoxic Levels for Trace Metals in Plant Leaves

Trace Metal	Normal Range (mg/kg)	Toxicity Range (mg/kg)	Toxic Doses to Plants (mg/kg)	Toxic Doses to Man (mg/kg)
Cd	0.1 - 2.4	1 - 30	-	-
Pb	5 - 10.0	30 - 300	3 - 20	1
Zn	1 - 400	100 – 400	60 - 400	150 - 600
Cu	5 - 20	20 - 100	-	-
Ni	0.02 - 5	10 - 100	-	-
Fe	-	-	10 - 200	200
Abdullahi et al., 2007				

There were no fruits from the tomato plants irrigated with water from control stone sub-base test rig and de-ionized water (figure 7). It was observed that Cd and Pb were undetectable in all the fruit samples analyzed. This was considered as an indication of good fruit quality achieved even after high dosing of pollutant on the stone and plastic sub-base test rigs to simulate worst case scenario.

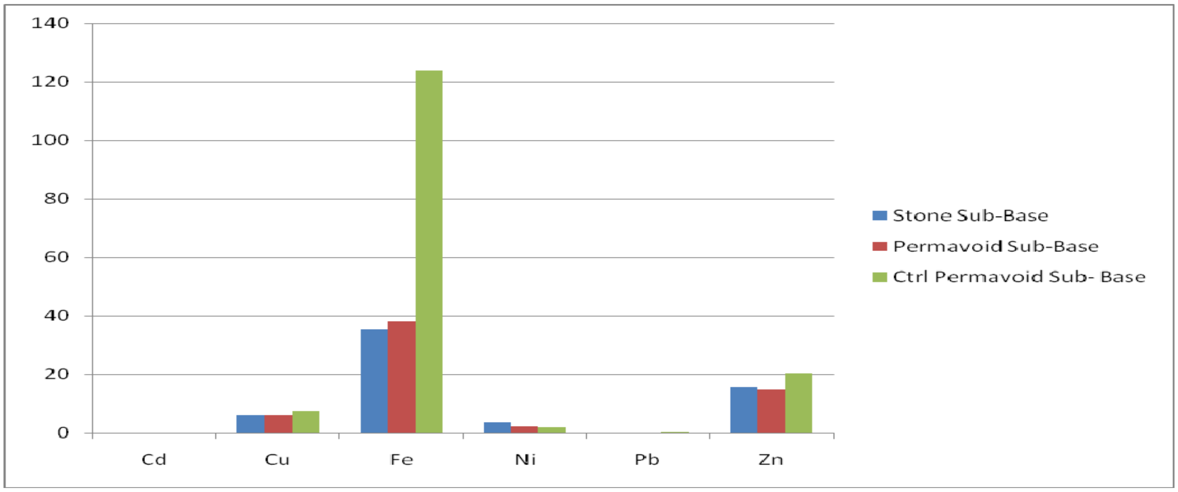

Figure 7 - Metals in Tomato Fruit

Furthermore, the levels of Cu, Zn and Ni remained at similar levels found in the leaves of the tomato plants (as shown in figure 7) and below the limits as shown in table 2. Fe concentration was < 40mg/kg in the fruits from tomato plants irrigated with water from the Stone and plastic test rigs, but high accumulation of Fe was observed (>120mg/kg) in tomato fruits from plants irrigated with water from Control plastic test models. However, these concentrations were within the normal range found in plant organs (table 4).

Table 4 - Concentration Range for Trace Metals in Edible Vegetables and Fruits (mg/kg)

	Cd	Cu	Pb	Fe	Ni	Zn
FAO/WHO[a]	0.02 - 0.2	-	0.5 - 1.0	-	-	-
Australian and New Zealand Limit[b]	0.05	-	0.01	-	-	-
EU Limit[c]	0.05	-	0.1	-	-	-
South African Limit[d]	0.1	30	1.0	-	-	40
Ramadan, 2007 (Tomato only)	0.1	4 - 40	-	25 - 300	-	-

[a] Abdullahi, 2007;
[b] Food Standards Australia New Zealand, 2003
[c] EU, (2006)
[d] South African Dept. of Health (2003)

3.3 Chemical Analysis of Plant Organs – Rye Grass

In the 1st and 2nd harvests (figures 8 and 9), it was observed that the concentrations of Cd, in rye grass that was irrigated with water from all the test rigs including DI water was within the normal range found in plant leaves in dry foliage (0.1 - 1mg/kg) (table 5) and below the FAO toxicity level of Cd in animal feeds (10mg/kg) (Aganga, 2005) as well as the maximum tolerable concentration by animals in dry diet (0.5mg/kg) (table 5). Also, Cu was within the normal range found in dry foliage (3 – 20mg/kg) (table 5) and below the FAO toxicity level of Cu in animal feeds (40mg/kg) (Aganga, 2005) as well as the maximum tolerable level by animals in dry diet (100 – 500mg/kg) (table 5).

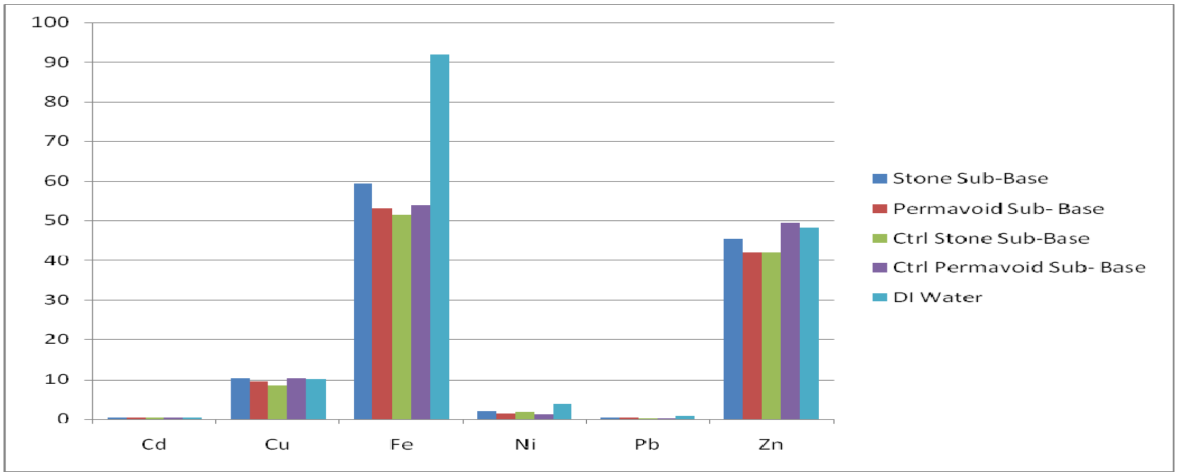

Figure 8 - Metals in Rye Grass (1st harvest)

The concentration of Ni was in the range of 1.4 – 3.69mg/kg in all the test rigs including DI water with the highest concentration of 3.69mg/kg observed in rye grass plants that was irrigated with DI water., but the concentrations were within the normal range of Ni in plant leaves as shown in table 1, normal level in dry foliage and below the maximum tolerable concentration by animals in dry diet as well as the phytotoxic levels in plants (table 3).

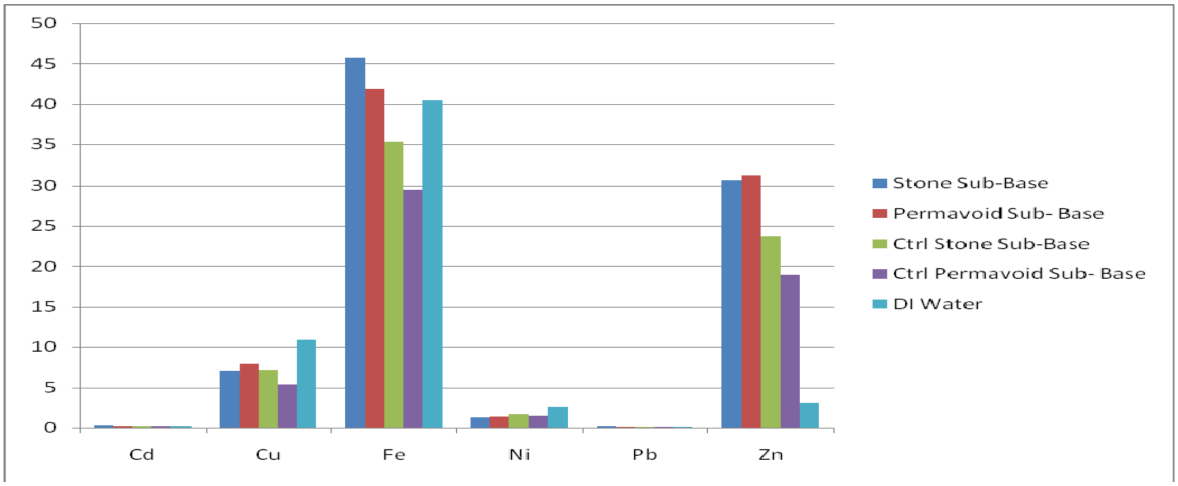

Figure 9 - Metals in Rye Grass (2nd harvest)

Table 5 Normal Ranges in Plants, Phytotoxic Concentrations and Toxic Levels for Livestock for Analyzed Trace Metals (from Chaney, 1989; aGupta and Gupta, 1998; $_{b}$Annenkov, 1982); Levels in Parentheses were Estimated (by NRC) by Extrapolating between Animal Species

			Maximum Levels Tolerated by Livestock (mg/kg Dry Diet)			
Element	Normal Levels (mg/kg Dry Foliage)	Phytotoxic Levels (mg/kg Dry Foliage)	Cattle	Sheep	Swine	Chicken
Cd	0.1 -1	5 - 700	0.5	0.5	0.5	0.5
Cu	3 - 20	25 - 40	100	25	250 300-500[a]	300
Fe^{2+}	30 - 300	-	1000	500	3000 5000[b]	1000
Ni	0.1 -5	50 - 100	50	(50)	(100)	(300)
Pb	2 - 5	-	30	30	30	30
Zn	15 - 150	500 - 1500	500	300 1000	1000 2000[b]	1000

Madejón *et al.*, (2002)

Similarly, concentrations of Pb observed were within the normal range of Pb in plant leaves (5 - 10mg/kg) as shown in table 1, normal level in dry foliage (2 - 5mg/kg) (table 3) and below the FAO toxicity level of Pb in animal feed (40mg/kg) (Aganga, 2005) as well as the maximum level of Pb tolerated by livestock (30mg/kg) (table 3).

Higher concentration of Fe was observed in the rye grass that was irrigated with DI water where the concentration was 91.96mg/kg compared to the range of 51.4 - 59.31mg/kg of Fe observed in rye grass that was irrigated with water from test rigs. However, these concentrations of Fe observed in rye grass were below the FAO toxicity level of Fe in animal feed (1000mg/kg) (Aganga, 2005) and within the normal range of Fe in dry foliage (30 – 300mg/kg) (table 3). The level of Fe in rye grass was also below the maximum level tolerated by livestock (500 – 5000mg/kg) (table 3)

4. CONCLUSION

This study has shown that in situations where water collected from, and stored under car parking surfaces receiving relatively large amounts of oil appears to be suitable for use as irrigation water from the point of lack of inhibition of seed germination, plant growth and development. It also seems that at least part of the fertilizer used to enhance biodegradation can be used a second time to enhance plant growth. The type of subbase seems to be immaterial when such effects are examined. Initial results indicate that the chemical nature of the irrigation water is such that it should not lead to problems of salinisation if used in hot climates. However the recycled nutrients provided in excess in an attempt to stimulate biodegradation in a pervious pavement may not be suitable in all circumstances. Further work is required to determine what additional nutrient additions would be required to ensure optimum growth for a range of plants.

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