Enhancing the Ecological Ability of Permeable Pavements Systems (PPS) as Urban Stormwater Green Infrastructure

Abstract: *Stormwater and urban surface runoff often transport contaminants such as hydrocarbons and heavy metals into natural watercourses and hydrosystems. A surge in impermeable surfaces covering natural vegetated surfaces is leading to an increase in flooding. Permeable pavement systems (PPS) such as a Sustainable Drainage System (SuDS) provides an ecological friendly solution in addressing the surge of stormwater runoff, surface water flooding an improving downstream water quality. Permeable pavement systems have emerged as a sustainable solution for stormwater management in urban areas. The principles of permeable pavements include providing a drainage system, improving water quality while maintaining a ground-bearing structure to transport vehicles. PPS are engineered to absorb, infiltrate, and attenuate a considerable amount of stormwater runoff to reduce flooding during storm events. These pavements additionally intercept pollutants because of their discrete particle retention capabilities. The filter media absorbs and remediates impurities, organic compounds, and hydrocarbons within the pavement structure. The research project focused on PPS enhancing stormwater quality which are also structurally viable, comparing subgrade and sub-base layers within the pavement structure and the ability to intercept various water pollutants and parameters from urban stormwater runoff. Two large-scale pilot PPS experimental rigs were designed, constructed, and tested according to British Standards guidelines for pavement designs (BSI, 2016) on the efficacies for improving stormwater treatment using low-carbon construction materials and recycled aggregates (gravel, pea gravel), sand and limestone. Stormwater was retained within the pavement structure for 30 minutes and 90 minutes analysing the outflow concentrations for operating temperatures, colour, pH, turbidity, nitrates (NO_3-)., and ammonium (NH^+_4). It was found that the effluent quality from the permeable pavements is notably superior to that of stormwater runoff without treatment because of the urban runoff impurities being trapped and remediated within the pavement structure. The mean removal efficiencies for turbidity, NO-3, and NH^+_4 for the pavement systems ranged from 28.2 %, 27 % and 9.2 % for PPS-1 and 21.8 %, 27.3 % and 16.1 % for PPS-2. The T-Test statistical computation for 2 Independent Means of the stormwater effluent at significant level of 0.05 (Two-tailed test) and OneWay Analysis of Variance (ANOVA) showed no significant differences in performance of the pavement systems*

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Keywords: *Ecological Stormwater Infrastructure, Sustainable Drainage Systems (SuDS), Low Impact Development (LID), Permeable Pavements, Water Circularity*

List of Symbols / Nomenclature

°C – Degrees Celsius
BMPs – Best Management Practices
BS – British Standards FTU –Formazin Turbidity
Units (FTU) MDA – Mechanistic Design Analysis
mg/L – milligram per Litre of stormwater
parameter
NH^+_4 – Ammonium ions
NO_3- – Nitrate ions
LID – Low Impact Development
PCU – PCU (platinum-cobalt units) for the measure
of colour
PPS – Permeable Pavement System
RM – Rational Method
SuDS – Sustainable Drainage System

1. Introduction

Urban stormwater management poses significant challenges due to increased impervious surfaces and limited natural infiltration. Traditional stormwater management techniques often fall short in adequately addressing urban runoff, resulting in pollutant discharge and water quality degradation.

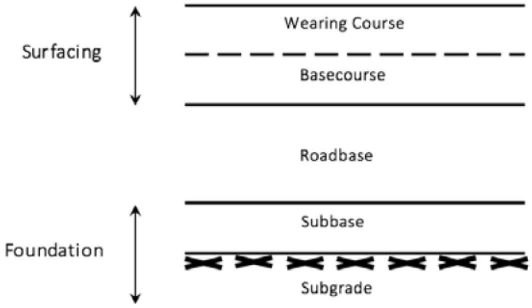
Pavements are located virtually everywhere to provide access to fundamental services through infrastructure to allow for the movement of people and goods. In engineering terms, a pavement is a reliable horizontal structure which is laid on to the ground, designed to distribute static and dynamic loads into the soil supporting the structure (Millard, 1971; Ridgeway, 1982; Yoder, and Witczak, 1991; Pavement Interactive, 2008). Soil distribution and particle sizes contribute to the bearing capacity of the pavement onto the soils (Thom, 2013). Permeable pavements can often appear to be very simple structures. Pavements are very complicated environmental structures. Permeable pavements are often used for airports, streets, highways, and parking lots (Ferguson, 2005; Thom, 2013). They are built to guard the subgrade from exaggerated deformation (Ferguson, 2005; Baxter and Walsh, 2011). These types of pavements can last for decades when correctly engineered with minimal maintenance (Stutzman, 1999). Each year around 10% of the UK's surfaces must be resurfaced due to structural and environmental deterioration. Impermeable areas can be minimised by employing constructed pervious surfaces for car parks and driveways. However, the inaccurate selection of construction and building materials and wrong depths can decrease permeable pavement life cycle (Stutzman, 1999). Therefore, for pavement engineers it is vital that the type of construction and materials used for proportion and design is well understood (Ridgeway, 1982; Taylor, 2000; Thom, 2013). Asphalt and concrete are both categorised as high-end construction materials applicable for permeable pavements (Sakai and Noguchi, 2012). Pervious surfaces can be either porous or permeable. They (permeable or pervious) pavements are constructed to allow rainwater/stormwater runoff to infiltrate through the surface and into the underlying construction layers, where stormwater is stored prior to infiltration to the ground, to be recycled or released to a surface watercourse or other drainage systems.

1) *Permeable Paving*: surfacing consisting of material that itself are impervious to water however, by virtue of voids through the surfaces, allows infiltration through the pattern of voids (Ferguson, 2005).
2) *Pervious Paving*: surfacing infiltrates water across the entire surface of the pavement material forming the surface for example, grass, porous concrete, and porous asphalt (Ferguson, 2005).

Currently, permeable pavement designs are relied upon learnt experiences and the use of modern techniques with analysis from computer methods (finite element analysis). The design of a permeable pavement features several layer combinations made up of different materials, hence the importance of understanding the material properties. The pavement material and thickness can be altered depending on the how it behaves during the analytical process (Christopher and McGuffey, 1997; O'Flaherty, 2002; Van Amsterdam, 2012). In addition, the design of paved surfaces needs to have adequate smoothness to ensure a high level of safety and to permit a practical speed (See Figure 1).

Over the past few years, it is becoming increasingly problematic with surface water flooding and the impact of impermeable surfaces, paving and drainage design. The term 'SuDS' or Sustainable Drainage Systems are engineered to manage stormwater runoff across the UK and Ireland (CIRIA, 2015). Stormwater runoff occurs when rainfall hits the surface of the ground and urban runoff often mobilises pollutants such as debris which are already on the ground surface (Netregs, 2014). Stormwater runoff flows into SUDS, which can impact the quality of the water. Poor water quality has the potential to affect aquatic habitats and human health. As most pavement materials commonly used today are impervious, leaked car oil and other harmful substances, remain on paved roads surfaces and flow directly into rivers and lakes causing contamination affecting the habitats of fish and other aquatic creatures. Floods are described as temporarily covered land, which is not normally covered by water and requires the appropriate types of infrastructure for best management practices (BMPs) as mentioned in by Sayers et al. (2012) and Sayers et al. (2016).

(a)



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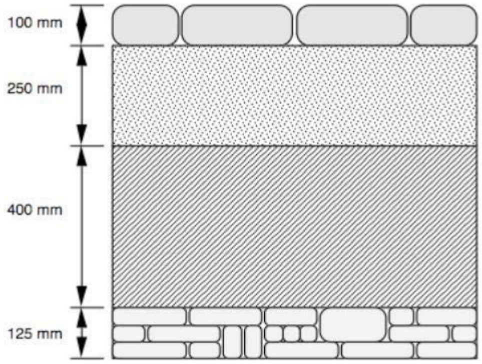


Figure 1. (a) Layers within a Typical Pavement and (b) Pavement Structure Thickness
Source: Adapted from Rogers (2008), Stutzman (1999) and O'Flaherty (2002)

Due to the increase in flood risk, the UK government implemented a “Future Water” scheme in 2008 for England and Wales, withdrawing the rights for building developers and contracting firms to connect infrastructure to existing drainage systems and there was clarification on the overall drainage system’s ownership and maintenance responsibilities. This “Future Water” scheme encouraged a less reliance on traditional drainage systems but several new-built do not include a Low-Impact Development (LID) through SuDS. Nevertheless, in 2016, the Environment Agency reported that floods cost England and Wales an estimated £270 million per annum (Environment Agency, 2018), reiterating the growing need for flood control and SuDS. Thus, SuDS reduce flood risks and stormwater run-off in an environmentally friendly way by mimicking the natural drainage systems. Infiltration systems such as PPS are ‘Green’ engineering or ecological engineering options to moderate the flows of stormwater in minimising flood risks whilst managing water pollutants onsite. SuDS such as PPS cater for more than one structural development to control stormwater runoff using a management treatment-train process (BRETT, 2018). PPS are being implemented for often to improve and enhance the overall integrated water management approach. Nevertheless, PPS contradict orthodox pavement construction techniques which has been used for around 2000 years (Van Dam and Taylor, 2009). The focus, compared to current practices is to get surface water away as quickly as possible, whereas porous or permeable pavement takes an opposite approach. The surface water is channelled into the pavement and stored or released into the surrounding environment. In urban areas across the UK, especially where heavy loads were generated from adjacent industry and especially from ports, the use of stone sett paving became the norm. Sett paving had two major advantages, firstly, they were resistant to the imposed load of stresses from the iron tyres of carts and secondly, they provided more grip for the feet of the horses pulling the carts as this was the mean of transportation at the time. The design of Sett paved stones consisted of hard stone in rectangular sections 150 mm x 250 mm deep in plan and typically 200mm deep. The Sett pavements were not placed directly onto the concrete, but onto a 12-20 mm thick bed of chippings or sand. The final layer is formed of clinker ashes which is a product of coal fired boilers and furnaces.

2. Permeable Pavement Design

Choosing a design life exceeding two decades involves considering long-term predictions relating to population growth, vehicle numbers and the volume of stormwater runoff (Interpave, 2010; McCormack, 2019). This is what is required for an effective permeable pavement design. Subsequently, permeable pavements do not fail unexpectedly however they progressively worsen in serviceability to a fatal level, which may be described as failure. The speed of deterioration regularly fast tracks as failure is approached. Engineers must develop the most economical arrangement of layers that will assure adequate dispersion of the incident wheel strength but simultaneously provide a drainage solution (McCormack, 2019). According to Interpave (2010), the major considerations of a permeable pavement design are:

- Structural design.
- Hydrological Design. - The materials forming the layers, and - Types and volume of vehicle traffic.

Motorised transport changed pavement design drastically as well as the use of rubber tyres. Speeds increased drastically, making safety a vital factor for permeable pavement design. Rubber-tyres extracts dirt from the road surface, releasing the stones and triggering blinding clouds of dust with high-velocity vehicles. Many pavement construction materials are designed using processed rocks (gravel, pea gravel) together with a binder. The primary role of the binder is to act as a lubricant so that the construction materials can be installed within layers and compacted to form a homogenous tier and the aggregate either undergoes chemical or cooling changes (NAPA, 2019). Where traffic loads are infrequent, the use of binder within the pavement structure is not necessary as the design of the unbound material can provide sufficient aggregate interlock once compaction has taken place.

The surface layer is the first layer of a pavement it is also an umbrella for the following layers: Surface course, Binder course and base. Any of these layers together (or separately) make the surface layer. These layers provide the structural elements to support the traffic loads and storm water loads on the standard foundation. The pavement surface itself forms the important skid resistant element and appropriate light reflectance for night-time commuting, driving, or cycling. Bituminous coated with a layer of fine asphalt or stones provide the surface elements (NAPA, 2019). This is typically the layer of materials below the surface course and above the subbase of the pavement; the purpose of a base course is to allocate the produced stresses from the loads so that it will not surpass the strength of the underlying soil levels. When the subgrade strength is low, the stress must be reduced to a low value and a thick base is needed. The subbase ought to be placed as quickly as possible once final stripping to formation level, to avoid damage from rain or sun, which might produce surface cracks. The fact that this is compulsory when pavements are constructed, highlights the significance of backfilling excavations quickly and accurately, thus preventing ingress of moisture when pavements may need excavating for utility and maintenance works. The pavement base is the central load bearing / load-spreading layer in the structure and is usually 100 mm or thicker depending on the loading.

The pavement's surface layer is a key structural zone which main functions are to endure applied loads induced from stresses and strains. The surface layer distributes the loads so that the pavement materials within the foundation layers do not become overloaded. This layer/ base also provides the pavement with added stiffness and resistance to fatigue, as well as contributing to the overall thickness, hence construction materials must always be used with a reasonably high quality.

Materials can be unbound soils or aggregates. Foundation layers are described as the tier at which excavation finishes and construction begins (it is the deepest point of the pavement structure). The role of the foundation layers is predominantly to provide a platform for the construction of the strong surface layers. The foundation layers provide the main structural element, with a thin surface course possibly made up of multiple surface dressings. Within the foundation layer, there are sub-layers (not applicable to all permeable pavement designs) with capping being one of them. Capping layers are merely levels of a certain fill materials. Often used on heavy applications, it normally consists of compressed rocks, placed in levels not surpassing 225 mm and completely crushed before laying additional layers. Clapping layers are a 'Development' layer, regularly placed above the subgrade to reinforce the present ground (McNally, 2017).

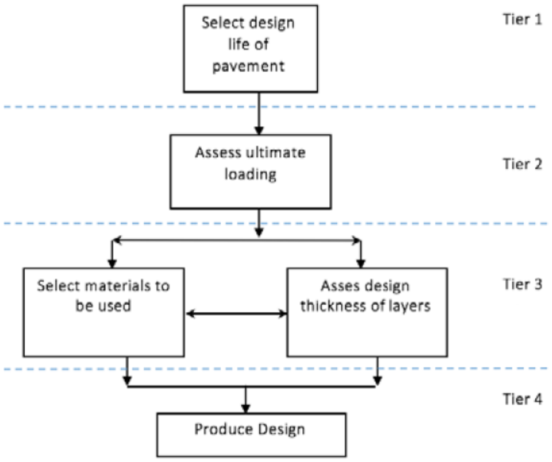


Figure 2. General Objectives for Pavement Designs
Source: Abstracted from Kendrick (1988)

Unless a subsoil is made up of rocks, it is doubtful it can be robust enough to carry the lightest of loads (Liu et al., 1983; McNally, 2017). Hence it is vital to superimpose further layers of construction materials to reduce the stresses incident on it. Permanent deformation can occur within the subbase layer if subjected to high loads. The shear strength and stiffness modulus are acknowledged gauges of the weakness of the soil to permanent misshaping. Soils with high values of both these characteristics are less likely to experience long-lasting deformation (Taylor, 2000; McNally, 2017). Nevertheless, these values can be reduced with the involvement of moisture content hence the importance to understand the type of materials within these pavement layers to determine the effective thickness. To determine the shear strength and stiffness characteristics of pavement materials a CBR (California Bearing Ratio) test is applied. The test involves a cylindrical plunger driven into a soil at a standard rate of penetration where the level of resistance of the soil is measured.

Subbase and capping together act as a regulator of the surface of the subgrade below and protect it against the effects of extreme weather. Along with the subgrade, they provide a platform on which the pavement can be built. For subgrades more than 5% CBR, the required depth is between 150-250 mm not exceeding the maximum depth. The thickness of the subbase layer is dependent on the shear strength and stiffness characteristics of the material used and then determined in accordance with the UK's Highways Agency - Design for Pavement Foundations HD 25/94 and CD 225. A pavement thickness should never be too thick nor too thin, otherwise it will fail to protect the underlying layers. For permeable pavements with the subgrade material with a CBR value less than 2.5%, a subbase depth of 150 mm must be used. If a material has, a CBR value of less than 2% the material is deemed unsuitable (Taylor, 2000).

Permeable pavements are frequently used as a stormwater management solution because of their aptitude to penetrate stormwater runoff. It is a necessity that the permeable pavement layer warrants precipitation to pass through to the underlying layers of the pavement structure. Hydrologic design is an essential and significant feature of any permeable pavement design and must be implemented to govern a satisfactory aggregate thickness, which is deep enough to provide the needed retention capacity for the design runoff volume. Hydrologic design is commonly based around the importance of storage volume to transitorily retain runoff. The retention volume of the total permeable pavement incorporates the volume within the subgrade layer, the subbase layer, and the pavement layer. After acquiring a value for thickness from both the hydrologic design method and the structural design method both are compared and then the highest value of the two is used.

In addition, it is possible to design a permeable pavement to infiltrate runoff within a preferred time frame. Although, within the permeable pavement industry, there is not currently a particular procedure of a hydrologic design. However, the rational method (RM) and Computer modelling method allow the total runoff to be calculated to determine the required thickness. The RM method is accurate when calculating peak runoff rates for smallscaled permeable pavements. When using RM, the time of concentration is to be equal to the duration of the design storm (Thompson, p. 2006). It is recommended to use computer modelling software (such as HydroCAD, Flood Hydrograph Package and HYDRUS) to calculate hydrologic designs of PPS. They are centred on two main points: (1) continuous simulation modelling program and (2) event-based hydrograph estimation (Rogers, 2008). Mechanistic design analysis (MDA) allows the prediction of pavement deterioration and has had major involvement within recent years. Mechanistic design methods are created on a theoretical examination of the stress induced in a pavement under load, mechanical properties of materials and experimental models of the materials under repeated behaviours alongside environmental conditions. Although MDA lacks real conditions, such as surface roughness and surface disintegration which are of significance to pavement maintenance.

These projections depend upon the predications of the rate at which the pavements will deteriorate and the effectiveness of maintenance methods with regards to loads experienced. This research project assessed the feasibility of low-carbon permeable pavement systems, to understand how structurally viable a permeable pavement is for urban and sub-urban infrastructure, to identify if the use of permeable concrete pavements can be sustainable.

3. Materials and Methods

For this study, several design considerations were considering. Various design factors significantly affect the ecological ability of permeable pavement systems. These include pavement type, aggregate size and depth, geotextiles, and infiltration capacity. Research shows that incorporating finer aggregates with increased surface area and choosing appropriate pavement materials have a positive impact on pollutant removal and infiltration rates (Del Grosso et al., 2019; Tota-Maharaj and Hills, 2023). Nature-based solutions (NbS) and vegetation integration within PPS can enhance their ecological functionality. Vegetation acts as a biofiltration layer, filtering pollutants and providing additional stormwater retention. Studies indicate that selecting suitable plant species, such as grasses and native vegetation, that can tolerate pavement conditions while maximising nutrient uptake and pollutant removal is essential (Monrose and Tota-Maharaj, 2018; Lee and Shin, 2017; Choi et al., 2017).

Moreover, maintenance and cleaning protocols continues to be a challenge with SuDS such as PPS. Regular maintenance and cleaning are crucial for ensuring the longevity and effectiveness of permeable pavement systems (Yang et al., 2022). Proper cleaning techniques, such as vacuum sweeping, are recommended to reduce clogging and promote proper functioning. Research emphasizes the significance of routine maintenance to prevent vegetation overgrowth, sediment accumulation, and pollutant build-up (Monrose et al., 2021; Zaqout et al., 2022). Permeable pavement systems have the potential to mitigate urban heat island effects through evaporative cooling. Pavement materials with high solar reflectance and thermal emissivity can reduce surface temperatures and improve urban microclimates. Selecting suitable materials is crucial to optimize thermal regulation benefits (Tota-

Maharaj et al., 2009; Tota-Maharaj and Adeleke, 2023). Enhancing the ecological ability of permeable pavement systems often requires the integration of multiple stormwater management practices. Combining rain gardens, bioswales, and green roofs with permeable pavement systems maximizes pollutant removal efficiencies and improves overall system performance (Huang et al., 2022; Hu et al., 2020).

3.1 Conceptual Designs

The conceptual designs of both permeable pavement rigs followed guidelines from the British Standards (British Standards 2015) on the guidelines for pavement designs including BS7533-13 (Site specific design standards and installation/construction standards). These are depicted in Figure 3.

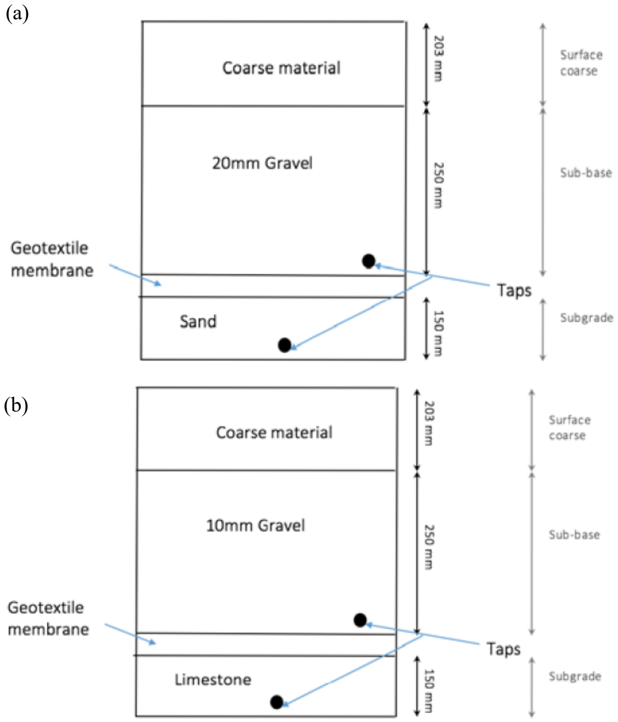


Figure 3. (a) Schematic of Pilot-Scale Permeable Pavement Design-1 (b) Schematic of Pilot-Scale Permeable Pavement Design-2 Source: After BSI (2016)

3.2 Construction Phase of Permeable Pavement Systems

The construction phase of the research project occurred at the Hawke Engineering Building, Civil Engineering Laboratory, at the University of Greenwich, Medway Campus, England, UK. Equipment and materials used for constructing all three pavements were as follows: Construction Equipment - Forklifts, three (3) 1 metre x 1 metre storage pods, shovels, buckets, measuring tools, sprit levels, taps, and drills. The construction materials included: Sand (1 tonne), limestone (1 tonne), recycled construction gravel 10 mm (1 tonne), recycled construction gravel 20mm (1 tonne), woven polypropylene geotextile membranes (Lotrak 2800), coarse material (1 tonne) and 150 permeable concrete blocks and pavement blocks.

Pavement rigs were cleaned prior to filling with various filter media to minimise errors and false readings when analysing stormwater quality datasets for infiltration periods. Stormwater effluents should be cleaner existing the various subgrade layers because of the filtration mechanism of sand, pea gravel and gravel. This can be verified by the changes in colour and turbidity between the inflow and outflow stormwater concentrations.

The process of filtration through a permeable pavement consists of stormwater passing through the various granular beds at relatively low fluid-flow speeds. The filter media within the pavement is expected to retain most of the suspended solids whilst permitting the remediated stormwater to pass through and continue to filtrate (Ingold, and Miller, 1988; Tota-Maharaj et al., 2009; Netregs, 2014; Tota-Maharaj and Paul, 2015). Additionally, the use of limestone in PPS-2 (Design two) was also embedded to compare the overall stormwater treatability rates. The chemical water quality parameters of concern to the environment can be impacted either negatively or positively with the use of limestone (rich in carbonates). This was investigated via any differential changes in pH of stormwater sampling as it exists the limestone layer, to determine if the effluent resulted in any significant pH alterations stemming from the previous aggregates (see Figures 4 and 5).

Geotextile fabrics within layers of permeable pavements is an effective means of intercepting debris passing through the pavement therefore improving water quality (Tota-Maharaj et al., 2010; Tota-Maharaj and Paul, 2015). After incorporating woven polypropylene geotextile membranes (Lotrak 2800, Don and Low, Angus, Scotland UK) in both PPS designs, it was clear these geotextile

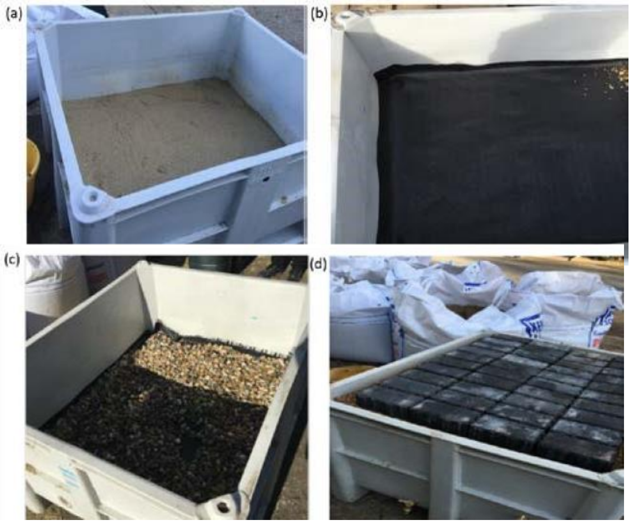


Figure 4. (a) Design one with Subgrade layer (sand) levelled), (b) Geotextile membrane fixed in place and (c) Sub-base layer filling and (d) 123mm of laying recycled coarse material placed, alongside 40 permeable blocks on Permeable Pavement System at the University of Greenwich, Medway Campus

Figure 5. (a) Interlocking Permeable pavements (b) Sub grade layer limestone after levelling (c) Subgrade layer, (d) Subbase layer and (e) Completed Pilot-Scale Permeable Pavement System at the University of Greenwich, Medway Campus

membranes reduced infiltration rate as less stormwater percolated and infiltrated out of both subgrade layers (the layers below the geotextile membrane).

However, this could be because of clogging of sediments on the membrane. Clogging occurs when debris are grouped together filling pores and void spaces within the pavement or in the geotextile membrane. To reduce clogging, periodic maintenance of the pavement is required. Maintenance techniques to reduce clogging includes high-pressured water to break the bonds formed within the surface layers or vacuum sweepers (Monrose and Tota-Maharaj, 2018). Nevertheless, it was observed that the water samples from the sandy layer of both PPS were considerably cleaner than that of the gravel zone.

3.2. Environmental Parameters and Stormwater Quality Analysis

When assessing the water quality of influent stormwater and infiltrated water, especially with respect to groundwater pollution, an issue that must be tackled is to limit any pollutants adding to the pavement during construction and whilst testing. To address this, controlled laboratory experiments were performed at the University of Greenwich, to limit any false readings. Comparing the two pavement designs (PPS 1 versus PPS 2) involved collecting data to determine which pavement design was more efficient in collecting pollutants from storm water run-off. This experiment focused particularly on water quality characteristics. These are:

1) *Physical Characteristics* - Properties often apparent to the observer such as colour, odour, and taste.
2) *Chemical Characteristics* - Parameters such as hardness, dissolved oxygen, and alkalinity.
3) *Biological Characteristics* - Natural waters containing protozoa, algae, and microorganisms.

Impurities found in stormwater can be classified as:

1) *Dissolved Solids* - Solids that dissolved in the water through or over the ground. Water may dissolve a variety of cations chemicals (such as calcium, manganese, iron, and potassium sodium) or anions chemicals (such as nitrates, sulphates, bicarbonate, and chloride). Different water sources upland/lowland can have adverse quantities of total dissolved solids (TDS). Derived minerals waterways may also dissolve man-made pollutants (such as, herbicides and pesticides). Where these are present, concentrations normally vary over the year.
2) *Suspended Solids* - Running water can carry debris, but simultaneously transport solid particles with greater density than water (such as suspended materials). The higher the velocity of water the bigger the particle. This is common in river water and stormwater runoff as they are more turbid during flooding. For example, a river with velocity of 1.2m/s can pick up and move shingles with diameters ranging between 25-75 mm.
3) *Colloidal Compounds* - Colloids are fine particles that do not settle, and which are electrically charged. The particles have a similar electrical charge, normally negative, which prevents them from merging together to form larger settle able particles. They are invisible to the naked eye but can convey elevated colour and turbidity levels within stormwater.

To test these stormwater quality parameters and urban runoff impurities several tests were carried out. Firstly, samples of rainwater and gully pot liquor was tested to record the pollutant levels of the rainwater which would enter the pavements at the same time. The only difference in this experiment was the materials used in the construction of the pavement. The stormwater parameters tested in this research project were according to the World Health Organisation guidelines on drinking water quality (WHO, 2006), the United States Environment Protection Agency - drinking water standards and health advisories (US EPA, 2018) and the European Union Council Directives concerning urban wastewater treatment (EU, 1991). These included: Colour, pH, Temperature, Ammonium (NH^{+}_{4}), Nitrates (NO_{3}-), and Turbidity for the influent and effluent of the pavement rigs. These parameters are a range of characteristics, which can be found in water and classified into the above categories of water quality (CIRIA, 2015).

4. Results and Discussion

Most full depth permeable pavement systems are designed and constructed to capture storm water and impurities from storm water runoff. The captured stormwater is usually stored in a subgrade aggregate base and eventually infiltrates into the subgrade soil. Design drawdown time usually ranges from 24 to 48 hours on a typical pavement. Extra stormwater that cannot be retained within the subgrade aggregate base during a storm event is usually discharged as effluent. The stormwater quality analysis and testing under controlled laboratory settings occurred after a drawdown period of 24 hours at two intervals of 30 minutes and 90 minutes, respectively.

On average, it takes approximately 15-20 minutes for organic matters to contact granular particles, hence a region of 90 minutes' retention time was slightly more effective than 30 minutes in the sampling regime. Table 1 summarises the results at different retention times throughout the experiments. As shown, the PPS 1 average removal efficiencies for turbidity, nitrates and ammonium were 28.2 %, 27 % and 9.2 %, respectively. A similar performance was observed for PPS 2 achieving comparable results with 21.8 % removal rates of turbidity, 27.3 % removal efficacies of nitrates and 16.1 % for ammonium. Figure 6 shows the variation in colour for the inflow and outflow was relatively low and negligible. There was a +/- of 0.3 PCU observed across all outflow colour recordings. However, at Stage 2 (with 90 minutes retention time), there was a slight decrease in the colour for the stormwater samples. PPS 1 reduced the colour value by 3.3 PCU, whereas PPS 2 sub-base layers reduced the mean fluent value by 3.4 PCU (i.e., no significant changes between both pavement systems). The colour checker has an accuracy of +/-5%. As a result, it is unclear to conclude which PPS showed an advantageous mechanism for the removal of colour.

As showed in Figure 7, both pavement systems showed a consistency with the influent and effluent pH values with a 2.5 % change across all experiments between the inflow and outflow stormwater. At 30 minutes: Gravel 20mm reduced the pH value slightly by 1.2%. Whereas permeable pavement system-2 had the same effluent pH value as the influent (8.1). After 90 minutes, pavement 1 continued to reduce the pH value, this time by a pH difference of 0.2. Furthermore, retention at 90 minutes, showed that gravel 10 mm had the matching effect on the pH value as gravel 20 mm did at 30 minutes of retention time. The pH values in pavement 2 were consistently similar because of the aggregates used. Pavement 1 gravel 20 mm showed no changes in effectiveness or alterations of pH values because of the larger surface areas for pollutants to stick too within the filter media. The pavement systems mimicked the stormwater treatment processes as reported

Table 1. (a) Permeable Pavement System 1 and (b) Permeable Pavement System - Average Inflow and Outflow Results across Various Filter Media Layers; Period of Analysis: January 2016-August 2019, Sample Number (N)=2700

(a) **Water Parameters**	**Influent**	**Retention Time after 24 hrs**			
		Effluent at 30 minutes		**Effluent** at 90 minutes	
		Stormwater Sampling and Position of Filter Media Layer			
		Gravel (20 mm particle size -Layer 1)	Sand and Limestone (Layer 2)	Gravel (20 mm particle size -Layer 1)	Sand and Limestone (Layer 2)
Colour	13 PCU	10 PCU	9.8 PCU	9.7 PCU	8.8 PCU
Temperature	12 (°C)	11.0 °C	10.0 °C	12.0 °C	7.0 °C
pH	8.1	7.9	7.8	8.0	8.0
Turbidity	11 FTU	8.9 FTU	8.8 FTU	8.0 FTU	7.9 FTU
Nitrates (NO^{-}_{3})	0.22 mg/L	0.21 mg/L	0.20 mg/L	0.18 mg/L	0.16 mg/L
Ammonium (NH^{+}_{4})	57 mg/L	53.5 mg/L	52.1 mg/L	50.5 mg/L	47.8 mg/L

(b) **Water Parameters**	**Influent**	**Retention Time after 24 hrs**			
		Effluent at 30 minutes		**Effluent** at 90 minutes	
		Stormwater Sampling and Position of Filter Media Layer			
		Gravel (10 mm particle size -Layer 1)	Sand and Limestone (Layer 2)	Gravel (10 mm particle size -Layer 1)	Sand and Limestone (Layer 2)
Colour	13 PCU	11 PCU	9.2 PCU	8.7 PCU	9.1 PCU
Temperature	12 (°C)	11.0 °C	11.0 °C	9.3 °C	9.8 °C
pH	8.1	7.7	7.9	8.0	8.0
Turbidity	11 FTU	9.0 FTU	8.3 FTU	8.5 FTU	8.6 FTU
Nitrates (NO^{-}_{3})	0.22 mg/L	0.20 mg/L	0.19 mg/L	0.18 mg/L	0.19 mg/L
Ammonium (NH^{+}_{4})	57 mg/L	54.6 mg/L	54.5 mg/L	51.2 mg/L	49.3 mg/L

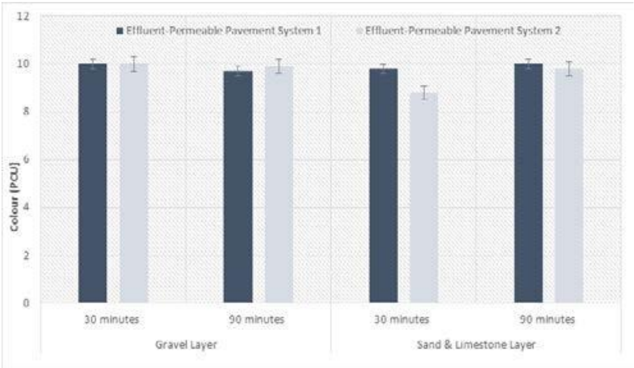


Figure 6. Comparison of Average Outflow Colour Concentrations through Gravel (left hand side) and Sand-Limestone Layers (right-hand side); Period of Analysis: January 2016-August 2019, Sample Number (N)=2700

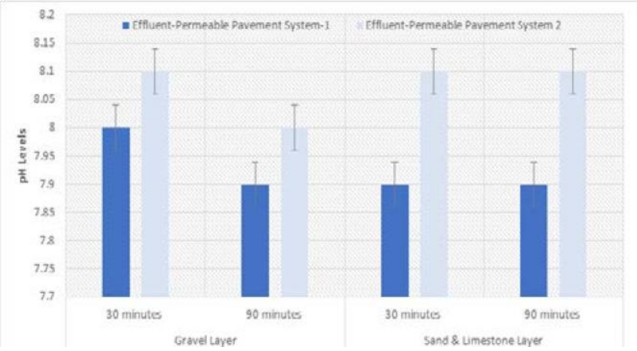
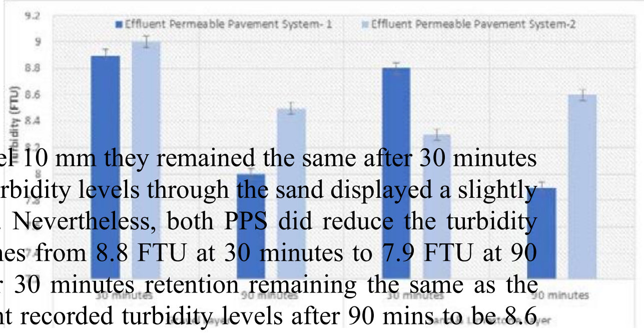


Figure 7. Comparison of Average Outflow pH Levels for PPS 1 and PPS 2 (Gravel Layer-Left Hand Side), Sand and Limestone Layer (Right Hand Side); Period of Analysis: January 2016-August 2019, Sample Number (N)=2700

by Tota-Maharaj and Scholz (2010, 2013).

For aquatic organisms in natural hydro systems, the best range for pH in water is within 6.0 to 9.0 (Tota-Maharaj et al., 2010). The pavement designs were effective in keeping the pH value within the range and these effluent pH values remained consistent throughout the different retention times. According to WHO (2006), the maximum permissible value of pH in drinking water should be 7.9. Similarly, the pH value also did not change while passing through limestone region at either retention (24 hours) and sampling times of 30 minutes and 90 minutes. The results were somehow unorthodox as stormwater passing through limestone should typically have high alkalinity levels because of limestone being rich in carbonates Limestone. An average, NO_3- (mg/L) of 0.22 was recorded across the entire period of study (see Table 1). Nitrates remained consistent throughout outflow of both pavements at the various sampling zones (with pH values as similar in Figure 6). Figure 8 illustrates the reduction of nitrate between the two-subbase layers. At 30 minutes gravel 20 mm nitrate reading remained the same while gravel 10 mm nitrate value changed by 0.01 mg/l. Moreover, at 90 minutes gravel 20mm reduced the nitrate value by 0.03 mg/L while the 10mm gravel reduced nitrate by 0.05 mg/L. As a result of the low inflow concentrations of nitrates, it was difficult to decipher whether the larger recycled gravel particles outperformed the other filter media after the 30 minutes or 90 minutes sampling period. For possible higher concentrations of nutrients, this type of SuDS would be an effective sediment trap, reducing the amount of nutrients, entering main watercourses (larger hydrosystems). PPS efficacies can provide mitigation against nutrient run off, thus larger surface areas of the aggregates with greater removal efficiencies were observed. At 30 minutes, the average outflow values recorded were 0.21 and 0.2 mg/L, whereas for the 90 minutes sampling period, a decrease of 0.05 mg/L was observed. At both 30 minutes and 90 minutes and through both layers gravel and limestone the average outflow values were 0.18 and 0.19 mg/L for PPS1 and PPS2, respectively. The percentage of error of the equipment (+/- 2 %) could explain the small concentrations of effluent readings as the values could fall with the margin. The mean Influent turbidity was computed at 11.0 FTU (see Table 1). Relatively small changes from the outflow turbidity readings were observed (i.e., 0.5-0.7 FTU). The turbidity passing through the gravel 20mm only fell by 2.1 FTU after 30 minutes retention, then at 90 minutes it fell a further 0.9 FTU which generated an average effluent turbidity of the gravel zone to be 8.4 FTU (see Figure 8).

Figure 8. Comparison of Average Outflow Nitrates (NO_3-) Levels for PPS 1 and PPS 2 (Gravel Layer-Left Hand Side), Sand and Limestone Layer (Right Hand Side); Period of Analysis: January 2016-August 2019, Sample Number (N)=2700



By comparison, to the levels of turbidity levels in the gravel 10 mm they remained the same after 30 minutes retention and only after 90 minutes the FTU fell to 8.6. The Turbidity levels through the sand displayed a slightly better performance overall in contrast to the limestone layer. Nevertheless, both PPS did reduce the turbidity levels. The sand reduced turbidity levels at both retention times from 8.8 FTU at 30 minutes to 7.9 FTU at 90 minutes. The limestone recorded no change in turbidity after 30 minutes retention remaining the same as the influent at 9.0 FTU. After the 90 minutes retention the effluent recorded turbidity levels after 90 mins to be 8.6 FTU (see Figure 9). The influent stormwater and gull pot liquor rainwater consisted of mean ammonium (NH^{+}_{4}) levels at 57 mg/l. The two aggregates performed as intended reducing the ammonium levels from 57mg/l at retention times (24 hours) and sampling regimes at 30 minutes and 90 minutes. The average effluent values for PPS 1 were 50.9 mg/L and 52.4 mg/L of ammonium for PPS2.

Figure 10 shows that the pavements succeeded in reducing the levels of ammonium. The gravel 20 mm performed marginally better at 30 minutes retention dropping the ammonium levels to 53.5 mg/l and then to 50.5 mg/l at 90 minutes. The gravel 10mm performed similarly with the gravel 20 mm has still dropped the ammonium levels from 57 mg/l to 49.3 mg/L. The sand and limestone layers managed to reduce the ammonium to 52.1 mg/l at 30 minutes and then 47.58 mg/l at 90 minutes. The limestone zone at 30 minutes recorded mean outflow values of 54.5 mg/l (at 30 minutes sampling) and then 49.3 mg/l after 90 minutes. This showed that an additional 60 minutes added in the ammonium breakdown within the pavement structure.

Figure 9. Comparison of Average Outflow Turbidity Levels for PPS 1 and PPS 2 (Gravel Layer-Left Hand Side), Sand and Limestone Layer (Right Hand Side); Period of Analysis- January 2016-August 2019, Sample Number (N)=2700

Figure 10. Comparison of Average Outflow Ammonium (NH^{+}_{4}) Levels for PPS 1 and PPS 2 (Gravel Layer-Left Hand Side), Sand and Limestone Layer (Right Hand Side); Period of Analysis- January 2016-August 2019, Sample Number (N)=2700

4.1 Statistical Hypothesis Testing for Stormwater Quality Observations

Table 2 presents the one-way analysis of variance (ANOVA) test and the F-statistic (the ratio of the variation between samples means) between the two PPS. As showed, the *p*-values are small (less than the alpha level). For temperature, the t-value generated was -0.21068 and the equivalent *p*-value was 0.838402, resulting in no significant differences for outflow sample temperatures.

Table 2. The T-Test statistical computation for 2 Independent Means of stormwater effluent at significant level of 0.05 (Two-tailed test) and One-Way Analysis of Variance (ANOVA) PPS 1 versus PPS 2 outflow samples. Degrees of freedom (n-1) = 2699.

Stormwater Parameter	T-Test statistical value	The p-value	F-statistic value
Temperature (°C)	-0.21068	0.838402	0.04439
pH	0.2357	0.819586	0.05554
Colour	0.05574	0.956914	0.00311
Turbidity (FTU)	-0.21481	0.956914	0.04614
Nitrates (NO_{-3} mg/L)	-0.15714.	0.879032	0.02464
Ammonium (NH^{+4} mg/L)	-0.55555	0.59371	0.30864

For the effluent colour parameter, *t*-test generated a value of 0.05574, and a *p*-value of 0.956914, leading to no significant differences when statistically tested at $p < 0.05$. Similar statistical results have been found with pH (a *t*value of 0.2357 and a *p*-value is 0.819586), turbidity (*t*value = -0.21481 and *p*-value of 0.835291), nitrates (a *t*value computed as -0.15714 with a corresponding *p*-value of 0.879032), and ammonia (a *t*-value of -0.55555 generated with a *p*-value = 0 .59371).

The water quality results showed that there were no differences (not significant at $p < 0.05$) between the both SuDS for the T-Test statistical computation with 2 Independent Means of stormwater effluent at significant level of 0.05 (Two-tailed test). The F statistic was used in combination with the *p* value for our study, when deciding if the overall results were significant. Using a significance level of 0.05, our sample data is enough to warrant any statistical differences between the two pavements.

4.2 Future Low Carbon Permeable Pavement Infrastructure and Sustainability

A sustainable approach is required when applied SuDS techniques such as PPPS with the overall goal of enhancing urban environments. Sustainable practices within drainage infrastructure can improve biodiversity, aesthetics, increase the environmental quality of the catchment and lower-long-term water resources consumptions, energy usage and costs. Permeable pavements play an important role across communities which can result in increasing the 'greening' effect and impact on society. Permeable pavements have the potential to become more carbon neutral and reduce hydrocarbons and other pollutants up to 80 % from stormwater runoff (Monrose and Tota-Maharaj, 2018; Monrose et al., 2021). Incorporating subgrade layers of low-carbon materials, recycled aggregates and geotextiles can have a positive impact on the overall carbon neutrality of the structure as well as provisions of water circularity (MatsGrids, 2019). The future of permeable pavement construction and materials used can explore greater than 70 % recycled materials and low-carbon construction (Monrose et al., 2021).

By using permeable pavements across communities in urban environments, it is foreseen in the short-to-near term future, that most traditional impermeable paving surfaces and conventional road and pavements will be retrofitted with green and eco-friendly technologies (such as permeable pavements). New urban developments are considering the use of sustainable and integrated water management approaches for creating a more sustainable environment for the future. It is feasible to retrofit and change impermeable paving surfaces to permeable and porous ones, as they will have greater effects to the wider society, communities, and regions. The advantages are obvious to the potential benefits of stormwater retention, attenuation, and treatment, thus creating healthier urban environments.

The implementation of permeable pavement in the future that can provide multiple benefits that may require integrated approaches (such as carbonation techniques) to advance the pavement's characteristics and reduce the carbon footprint. There are advantages for using permeable pavements with photocatalytic coasting or photochemical cements which can result in reducing road emissions and improving the health and safety of the environment (TotaMaharaj and Scholz, 2010; Tota-Maharaj et al., 2010).

5. Conclusions and Outlook

Recently, many meteorological reports have showed higher rainfall and unpredictable patterns causing increased surface water flooding and the greater need for SuDS. Regardless of our modern and high-quality research presented in this paper, it is safe to conclude that PPS are an essential aspect within drainage infrastructure (SuDS) and plays a vital role within the built environment. Generally, both pavement designs (PPS 1 and PPS 2) were relatively effective for stormwater treatment, improving the outflow water quality.

Having regards the pilot-scaled experiments carried out throughout this project, it was difficult to establish whether the pavements showed any significant differences in the treatability and variations of pH, colour, nitrates, and ammonium. The permeable pavement experimental rigs, displayed its applicability and sustainability for urban environments due to its effectiveness in decreasing the overall stormwater volumetric loads, support surface water infiltration into the ground and natural hydro systems, decrease the quantities of water pollutants transported downstream to nearby water courses, storm drains and reduce the flow velocities of stormwater thus significantly reducing the risk of flooding. The aggregates used for constructing permeable concrete pavements have an important effect on the sustainability of the pavement as the transportation of materials and production have a large carbon footprint and impact. Constructing and manufacturing permeable pavement blocks with recycled materials (such as concrete rubble) can create an ecologically friendly pavement system.

Moreover, as clogging is a repeating issue within permeable pavements, engineers tend to shy away from applying appropriate maintenance mechanism to these structures within them to the relative urban environments. Nonetheless, with appropriate preservation, consisting of regular vacuuming of the surface to prevent clogging by sediment, permeable concrete can have a minimum service life of two decades.

Permeable pavement systems have demonstrated substantial potential as urban stormwater green infrastructure. They can play a significant role in sustainable stormwater management in urban areas Future work would be related to low-carbon materials, and pavement structures utilising higher content of recycled construction materials, mimicking variable loads onto the pavements, and examining its structural integrity. Stormwater runoff consists mostly of heavy metals, hydrocarbons, and other pollutants (such as, faecal coliforms and organic loadings) which can be looked at in further details when combined with low-carbon permeable pavements. To gain further insights and results on lowcarbon permeable pavements, experiments and tests should be performed over a longer duration for getting thorough analysis of this environmental infrastructure. The ecological ability of permeable pavement systems can be enhanced with careful design considerations, vegetation integration, maintenance protocols, temperature regulation, and combining practices. Further research is needed to investigate long-term performance, cost-effectiveness, and scaling-up of these systems.

Acknowledgements:

The authors would like to express their thanks and gratitude to the technical staff's support at the University of Greenwich, Department of Engineering Science, Medway Campus, England, UK, and the financial support from the International Water Security Network (ISWN) and the Lloyds Register Fund.

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