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Improving Stormwater Infrastructure with Low-Carbon SuDS: A Comparison of Porous Asphalt versus Interlocking Permeable Pavements

Kiran Tota-Maharaj [a,Ψ], Colin Douglas Hills [b], Hazi Mohammad Azamathulla [c],
Blessing Oluwaseun Adeleke [d], and Ghassan Nounu [e]

[a] Royal Agricultural University, Cirencester, Gloucestershire GL7 6JS, United Kingdom;
Email: Kiran.Tota-Maharaj@rau.ac.uk

[b] Indo: UK Centre for Environment Research and Innovation, and the Centre for Contaminated Land Remediation, University of Greenwich, Chatham Maritime, Kent, ME4 4TB, UK Email: c.d.hills@gre.ac.uk

[c] Faculty of Engineering, Department of Civil and Environmental Engineering, University of the West Indies, St. Augustine, Trinidad and Tobago, West Indies. Email: Hazi.Azamathulla@sta.uwi.edu

[d] School of Engineering, Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd CF37 1DL, UK. Email: blessing.adeleke@southwales.ac.uk

[e] School of Engineering, College of Arts, Technology and Environment, University of the West of England, Bristol BS16 1QY, UK. Email: ghassan.nounu@uwe.ac.uk

Ψ *Corresponding Author*

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Abstract: *Climate change resulting in frequent flooding events have caused catastrophic effects to Small Island Developing States (SIDS) in recent times. Rainfall events have become less predictable in recent years. This paper presented the findings of a project that evaluated permeable pavement systems (PPS) using low-carbon materials, recycled aggregates, and carbon-negative aggregates within its structure as a sustainable drainage system (SuDS). It replicates typical drainage systems, reducing the surface runoff volumetric rates and retaining stormwater pollutants from downstream runoff. Low carbon permeable pavements and Carbon Negative pavement systems are novel structural pavements implementing materials which can withstand the same axial loading as the conventional pavements and can enhance stormwater quality by water treatment through filtration and infiltration between sub-base layers. Carbon-negative aggregates utilise patented technology that converts secondary waste products into high-quality aggregates based on a process that absorbs CO_2 into the pavement materials. This paper evaluates two pilot-scaled Low-Carbon-Porous Asphalt Pavement (LC-PAP) systems versus two carbon-negative interlocking concrete block permeable pavement systems (CN-ICB-PPS) on the overall environmental and structural performance. It was found that the pavement systems achieved similar permeability for stormwater remediation results using a combination of virgin aggregates, recycled aggregates, and carbon-negative aggregates for the CN-ICB-PPS and LC-PAP. The pavement systems utilising greater content of carbon-negative aggregates displayed a higher water infiltration rate when compared to the CN-ICB-PPS because of the sub-base design implemented. The LC-PAP systems could achieve the necessary strength at a lower cost, implementing low-carbon recycled materials and carbon-negative aggregates forming 70 % of sub-base layer of the pavements. For the LC-PAP system, ammonium, nitrates, colour, BOD and COD from the stormwater influent decreased significantly when compared to outflow water samples from the CN-ICB-PPS. Due to the variations in the top layers of the pavements with very small pore-spaces, this ensured a greater pollutant retention rate improving the overall stormwater quality being discharged from the pavement. The CN-ICB-PPS displaced a slight decrease in ammonium, nitrates, and colour over the period of study. Moreover, the LC-PAP contained higher content of low-carbon materials and recycled aggregates, placed above the saturation zone of the pavement, allowing some stormwater pollutants to filtrate easily through the pavement structure.*

Keywords: *Porous Asphalt; Environmental Monitoring; Resilience; Sustainable Drainage Systems (SuDS); Flood Management*

1. Introduction

Asphalt, tarmac, and pavements are still the main source of construction materials for roads, highways, pedestrian pathways, and other forms of transport infrastructure used today. Pavements and asphalt are the main sources that are used daily for any kind of transportation. Starting from light weights for pedestrians to heavy weights for cars and trucks. Among the past decades, all the hard surfaces have

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been experiencing deterioration and are being repaired every now and then. This is a significant reason for all the research and developments that have been taking place in the pavements sector. The deterioration that has been occurring in pavements can be identified, because of misguided methodologies, in choosing the right structural design, leading to poor material selection or inaccurate axial designs that led to subpar sub-base structures (Renard et al., 2021). The Asphalts and pavements can fail and collapse in various ways as bleeding, block cracking and spalling. Block cracking and spalling can result from the heavy loads that is exerted by the runoff water on the surface of the pavement. Low-Carbon pavements or paving systems incorporating carbon negative aggregate and carbon-negative materials encompasses a novel design and methodology for the pavement industry. The manufacturing of the concrete blocks always emits significant CO_2 in the production process.

In recent decades, technologies have taken place and new green approaches have been considered. The UK manufacturers of concrete blocks have achieved low carbon footprint per m^2. However, in manufacturing concrete blocks for big scales sites as 1000s of m^2, the carbon footprint will eventually be considered high (Peng et al., 2015). The Asphalt manufacturing process emits CO_2 in the production different stages. The heat energy that is produced from the asphalt mix also produces gases that contain CO_2 or some other gases equivalent to CO_2 as N_2O, which is equivalent to 310 CO_2 (Peng et al., 2015). The life cycle of green-house gases produced from the production process of asphalt first takes place at the construction phase, including all relevant construction management processes, machinery and fuels used. The UK manufacturers of concrete blocks have achieved low carbon footprint per m^2. However, in manufacturing concrete blocks for larger scale sites of 1000s of m^2, the carbon footprint will eventually be considered high (Peng et al., 2015). The Asphalt manufacturing process emits significant volumes of CO_2 in the different stages of production. The heat energy that is produced from the asphalt mix also produces gases that contain CO_2 or other gases equivalent to CO_2, such as N_2O which is equivalent to 310 × CO_2 (Peng et al., 2015). These gases are produced from the construction, construction process, machinery and fuels used (see Table 1).

1.1 Pollution in Urban Surfaces

The urban surfaces across cities, towns and villages include streets, parking lots, roads, highways, and pedestrians' pavements (Hvitved et al., 2010; Xu et al., 2016). The pollution caused in these areas is often referred to as land use pollution. Whether it is the pollution caused by mobile facilities or due to mobile facilities. These types of pollution may include oil leaks, vehicles exhaust, soil erosion, as well as related pollution from the living hood, and the road materials (Hvitved et al., 2010; Lehmann, 2014). When high volumes of rainfalls take place in urban cities with massive pollution, the pollution that is produced will continue growing, and thus, be transported overland to receiving waters. The pollution that occurs in individual parking lots, roads, or streets might be minor but on a significant scale in big cities, it is hard to monitor. Since the roads are made by impermeable pavements, the contamination is kept flowing on the roads with the toxics, suspended solids and dangerous nutrients polluting the whole community (Lim and Lu, 2017).

1.2 Stormwater Management

This a phrase that is used globally, but each country develops it on its own way such as low-impact development, sustainable drainage systems, water-sensitive urban designs (Tota-Maharaj 2010, Tota-Maharaj et al., 2012, Tota-Maharaj et al., 2021). Sustainable stormwater management must meet certain levels of hygiene to be used for either human use as drinking water (potable consumption), or agriculture use for crop growth and development. If not, then the water will be considered as grey water, and the uses will differ. Across urban cities where the population growth is rapidly high, the usage of water exceeds the normal supply, thus sustainable water management is essential and is more common to be implemented. Moreover, the cities that are facing climate change and are experiencing many dry seasons are encouraged to make the sustainable water resources management more applicable (Russo, et al., 2014).

The solutions to be developed are collection of rainfall and stormwater and regenerate the grey water to be used again in some fields that are not in direct contact with human activities. The stormwater is vital factor of the

Table 1: The Amount of Carbon Emitted in Various Phases of Producing and Manufacturing the Asphalt

Phase of Asphalt Manufacturing and Application for Roads/ Pavements	Phase I (%) - The asphalt heating process with coal and aggregate heating process with heavy oil	Phase II (%) - Asphalt heating and aggregate heating process with heavy oil	Phase III (%) - Asphalt heating and aggregate heating process with natural gas
Aggregate Stocking	1.14	1.23	1.63
Aggregate Supply	0.84	0.77	1.37
Aggregate Heating	65.39	96.00	65.36
Asphalt Heating	15.24	14.93	13.00
Mixture mixing	12.87	10.33	13.67
Mixture transport	0.14	0.78	0.12
Mixture paving	1.52	1.46	1.80
Mixture rolling	2.63	2.21	3.04

Source: Abstracted from Peng et al. (2015); Aggregate Industries (2018) reused water especially in the high dense urban cities. The dynamics that must be considered in water management are, firstly not all types of water need the same treatment, and secondly not all usage activities require the same amount of water. These two dynamics will save a lot of water and will be more economically in water purification methods. For the cities, that have some seasons with high rainfall and other dry seasons, the rainwater storage and harvesting will be an ideal method to reuse the water in other seasons (Russo et al., 2014). The sustainable drainage systems are manufactured to alleviate contamination that appears due to rain runoff. The main idea is replicating the previously used drainage system to treat the runoff and remove or reduce the contamination (Wilson et al., 2004; Tota-Maharaj and Hills, 2023).

1.3 Benefits of SUDS

Benefits of SUDS may include: 1) building a system that is similar to that of the natural drainage infrastructure, and any upcoming modifications to the natural drainage systems are decreased, 2) eliminating or even diminishing the water discharge from urban parts to the sewers to substitute the natural drainage systems as well as decreasing the overflow of water, 3) enhance the quality of water to the common existing wastewater sewers by performing normal cleansing to the source of pollutants and removing all the toxins, chemicals, and contaminants from water in both the rural and urban parts of the countries, and 4) enhance the wildlife environments.

1.4 Low-carbon Permeable Pavements and Porous Asphalts

Low-carbon permeable pavements and porous asphalts are most economical, practical, and environmentally friendly way of storm management (Eurovia, 2019). The world is adopting a new direction of new sustainable, zero and carbon negative techniques to benefit the world and reduce the Global warming. The urban cities unlike the rural cities are facing high levels of carbon dioxide (CO_2), thus a plan to reduce CO_2 emissions was acted upon by the UK government since 2008 with a target to reduce by 26% in 2022 and 80 % by 2050. The infrastructural projects make up a huge part of the 2050 plan for zero carbon UK. There has been a high support in its building and environmental regulations in the UK. According to Part H3 of the building regulations of England and Wales, it requires a water, rainwater, and permeable pavement for water discharge in the infiltration system (Interpave, 2010). In the UK, a new building regulation has been introduced in 2016 for new zeros road map. Furthermore, referring to the Scottish building standards, Section 3 discusses the usage of SuDS that the net zero-carbon permeable pavement is one of the essential cores of the SuDS (Interpave, 2010).

The carbon negative permeable pavement system (CN-PPS) and the Low-Carbon-Porous Asphalt Pavement (LC-PAP) systems relay its foundation on controlling stormwater and absorbing the rainwater to get the water away from the pavement as rapidly as possible. The sustainable and environmentally friendly pavement system is created not only to retain the CO_2 from rising but its intake of CO_2 in the manufacturing process more than the CO_2 emitted. The interlocking concrete block permeable pavement systems (CN-ICB-PPS and LC-PAP are built up of different materials, the upper surface is either concrete blocks or asphalt, depending on the requirements. The sub-base materials will differ depending on the type of the upper surface, especially when applicable to sustainable pavement drainage systems (Chu et al., 2023).

There are some common materials as the laying course of graded aggregates. The aggregate materials must be within the British standards. The jointing and voids materials can be similar to that of the laying course of graded aggregates. In the scenario of heavy traffic site, some hydraulic bounds should be installed. Moreover, the layers at the bottom are Dense Bitumen Macadam, geotextiles and lastly capping (Interpave, 2010). The permeable pavement system is considered one of the leading technologies of the SuDS. The drainage system is made from series of techniques that reduce the influences on the environment. The SuDS is a new way of thinking on how to use the runoff water, greywater, or wastewater efficiently to benefit the surrounding environment (Tota-Maharaj et al., 2021). This project evaluated novel designs that combined traditional SuDS with low-carbon construction materials and carbon-negative aggregates to achieve a very eco-friendly pavement system. This low-carbon pavement system can replace conventional impermeable road and pavement materials, mimicking natural hydrology and drainage conditions. Such porous and permeable paving systems can allow stormwater and urban runoff stemming from heavy rainfall events, attenuating volumetric flows, and restricting surface flooding, as well as remediating pollutants within stormwater from entering urban water and wastewater treatment works (UNHSC, 2009; McCormack, 2019).

This project aims to (i) develop a low-carbon and/or carbon-negative permeable and porous paving systems (interlocking concrete block permeable pavement systems (CN-ICB-PPS) and LC-PAP); (ii) measure the efficacies of such paving systems on its abilities to reduce stormwater runoff, intercept, and treatment stormwater with varying flowrates and (iii) evaluate the opportunities for stormwater recycling from a water circularity approach, preventing stormwater diversions within urbanised areas. The project focused on the impacts of designing, testing, and evaluating such low-carbon permeable and porous paving systems and their impact on the environment. It compared both Porous Asphalt Pavements (LC-PAP) versus Interlocking Concrete Block Pavements (CN-ICB-PPS) as a SuDS and their abilities to enhance urban stormwater runoff improving the water quality and the impact of the sub-base and subgrade layers of the pavement systems.

2. Materials and Methods

Four (4) low-carbon asphalt porous (LC-PAP) and carbon-negative interlocking concrete block permeable pavement systems (CN-ICB-PPS) rigs were designed and constructed in accordance with British Standards (BS 7533-13: 2009) Guide of permeable pavements constructed with concrete paving blocks. The structural design of the concrete pavement makes dual roles, as the same aggregates that are used to allow the water to pass through are those which strengthen the pavement to withstand the traffic loading (Interpave, 2010, 2012).

2.1 Interlocking Permeable Paving Blocks

The Paving Blocks are made of Concrete that are bespoke manufactured for the permeable pavement. The concrete blocks are certainly designed to allow the water to travel through them by using widely number of holes or by the spacing between the blocks. The Permeable blocks are 80 mm thick and are made in accordance with BS EN1338: 2003 – '*Concrete paving blocks – Requirements and test methods*' BSI 2003 (Interpave, 2010, 2012; Scholz, 2014).

2.2 Porous Asphalt

The porous asphalt has different mechanical properties, and they depend on the different sizes of the aggregates used on the top surface (Bérengier et al., 1997). There are different sizes for the asphalts aggregates; however, the most commonly used ones are 10, 14, and 20 mm, respectively. Aggregates Industries Company manufacture the Permeable asphalt types that are considered above (Aggregates Industries, 2016). The porous asphalt main mechanical properties are Air Voids, Indirect Tensile Stiffness Modulus, Retained Stiffness, and the hydraulic Conductivity. The 20mm Specifications Asphalt specification (Pavement interactive 2012; Aggregate Industries, 2018) as used for porous asphalt paving system 1 and the 10 mm Specifications Asphalt specification was used for porous asphalt paving system 2 (Pavement interactive 2012; Aggregate Industries, 2018).

2.3. Laying Course Materials

The concrete blocks were fitted on laying coarse material that passes the 6.3 mm sieve and retains on the 3 mm sieve. The laying course material should be coarse enough to permit the water discharge to pass through it. In accordance with British standards BS EN 13242: 2002, the laying course material and particle sizes should be within 2 mm to 6.3 mm, respectively. It is allowed to have some particle size over 6 mm and some under 2 mm, but these particles must be in very small proportion (Interpave, 2010, 2012; Scholz, 2014). Hydraulically bounded aggregates are usually added in the permeable pavement system faces heaving trafficking. The Hydraulically Bounded Aggregates can use Particle Size Distribution limits, and they must comply with BS EN 14227-1: 2004 for hydraulically bound mixtures (Scholz, 2014).

2.4 Pavement Sub-base

The permeable base is the most essential hydraulic and structural layer as it holds the strength and the stiffness of the pavements. This layer is mostly made of coarse-graded aggregates (CGA), the sizes of the aggregates in this layer are a mix that varies from 5 to 20 mm. If heavy traffic scenarios would act on the pavement, hydraulic bounded coarse aggregates should be included, accompanied/ or replacing the coarse graded aggregates. That will enhance the performance of the pavement to withstand the traffic loadings. The CGA must follow BS EN 13242: 2002.

To ensure a high level of firmness and stability, hard crush aggregates are more effective for installation. The particle size distribution for sieve sizes forms 2 mm to 40 mm (Interpave, 2010, 2012; Scholz, 2014). The Sub-base of the porous asphalt paving systems consisted of 6 different materials. The first layer is thick dense layer of crushed stone with a desired thickness of 150 mm. The second layer consists of virgin aggregates of undistributed aggregates sizes that varies from 5 to 20 mm. The third layer is called the filter blanket; it is the thinnest layer amongst all the layers only. This layer is made of pea gravel, and it can be thickened to replace the fourth layer depending on the underlying material and the storage capacity. The Fourth layer is reservoir course, which is made of series of recycled aggregates from the built environment industry and the wider civil engineering sectors. This layer is mostly made of crushed concrete and other SuDS materials. The fifth layer is a carbon negative aggregates overlying a layer of crushed quarry scalping. Below this layer the draining pipes are found. The existence of air voids in the sub-base layers is not preferred as the air voids acts as obstructions to the vertical discharge of water to the lower layers (University of Hampshire Stormwater Centre, 2009). Lastly, the native materials were placed at the bottom (Chopra et al., 2014).

2.5. Hydraulically Bounded Aggregates

Hydraulically bound mixtures are aggregate mixtures incorporating binders based on cement, lime, gypsum, and fly ash. For hydraulically bounded aggregates, due to the hydraulic reaction which hardens and binds the mixtures in the presence of water, provides elevated stiffness and increased strength to the pavement structure. Hydraulically bound aggregates have been used in numerous paving applications and offerings significant benefits over conventional pavement systems such as (i) Containing 100 % recycled aggregates and (ii) Mixtures allowing the re-use of construction site materials (granular).

2.6 Recycled Construction Materials

The recycled construction materials as a capping material were used merely for the No-Infiltration Systems. The capping layer is usually made of quarry scalping, hard-core and crushed concrete. They are used to ensure a strong platform and to resist movement of any particles from the above layers. Moreover, it is requirement of the National Highways, formerly the Highways Agency in England. The capping materials usually are stiff and BR of minimum Cm 15 % (Interpave, 2012; Tota-Maharaj et al., 2012).

2.7 Geotextile Membranes

The geotextiles are thin membrane that can be installed either in the upper part, lower part, or both in the permeable pavement. One of the important characteristics of the geotextile membrane is to enhance the growth of the microorganisms, which allows the biodegradation of the hydrocarbon's contaminations in the permeable pavement (Tota-Maharaj, 2010). Besides, the geotextile, membrane can retain the penetration of oils to the lower layers of the permeable systems (Pratt et al, 1999). The holes that are located within the geotextiles varies in sizes from 0.508 to 0.0508 mm. These holes approximately consume 1/3 from the total geotextile surface (Tota-Maharaj et al., 2012). The geotextiles are used in the interlocking concrete block permeable pavement systems (CN-ICB-PPS) in line with the British standards BS EN 13252: 2001 and BS EN 13249: 2001 (see Figures 2-4).

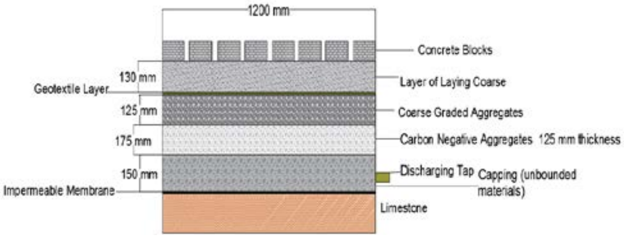

Figure 1. Schematic for Interlocking Permeable Pavement Block System

Figure 2. Experimental Rig for Interlocking Permeable Pavement Block System Constructed and Tested at the University of Greenwich, Medway Campus, England, UK
(Period of Analysis 2016-2018)

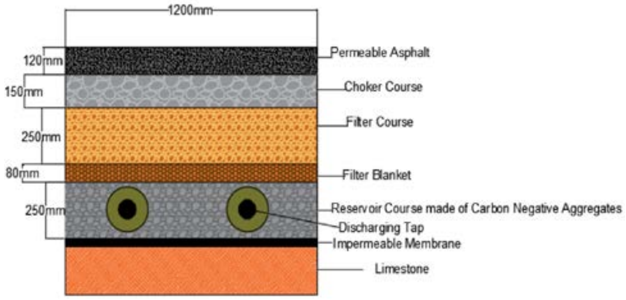

Figure 3. Schematic for Low-Carbon-Porous Asphalt Pavement (LC-PAP)

Figure 4. Experimental Rig for Low-Carbon-Porous Asphalt Pavement (LC-PAP) Constructed and Tested at the University of Greenwich, Medway Campus, England, UK
(Period of Analysis 2016-2018)

2.8 Carbon Negative Aggregates

The carbon negative aggregates sizes were 15 mm aggregates, they are manufactured using certain technology that pumps carbon dioxide in the manufacturing process than the whole carbon emitted. Table 2 shows the specifications low-carbon and carbon-negative aggregate. The carbon-negative aggregates are made from wastes materials resulting from the construction industry. The carbon-negative aggregates are more sustainable solution with added value for the to the pavement sector, as it is cheaper in cost, having more environmental benefits. The amount of CO_2 that is captured from the air for the necessary number of aggregates needed in the rig is 12 Kgs per m^2. The key advantages of the carbon negative aggregates:

1) Using carbon-negative aggregates reduce the production of greenhouse gases, thus it helps in reducing the global warming if used in massive quantities.
2) They provide lower density; however, they produce more strength than some virgin aggregates as Limestone.
3) Using the carbon-negative aggregates helps in saving thousands of tonnes of virgin aggregates annually.

2.9 Stormwater Quality Analysis

The experimental rigs built using Carbon Negative Porous Asphalt and Low-Carbon Permeable Pavement Systems were tested on their capabilities for stormwater treatment

Table 2. Low-Carbon and Carbon-Negative Aggregate Specifications

Particle Size and Type	0-15 mm	Standards (Eurocodes/ British Standards)
Dry loose bulk density	Minimum 950 kg/m^2 Maximum 1100 kg/m^2	EN 1097
Particle Density	Over dried 1.94 kg/m^2	EN 1097
Crushing Resistance	Typical Value: 6.6 N/mm^2 Minimum value: 5.2 N/mm^2	EN 13055
Moisture content as delivered	Typical value 8 %	EN 13055
Water Absorption	18.8 %	EN 1097
Water soluble chloride	4.2 %	EN 1744
Water soluble sulphate	0.1 %	EN 1744
Total sulphate SO_2	1.78 %	EN 1744
Resistance to Attribution (Los Angeles)	39 %	EN 1097
Magnesium Sulphate soundness	30.1 %	EN 1097
Drying shrinkage	0.021 %	EN 1097

and remediation. These stormwater quality tests were important in verifying these pavement rigs capabilities for using recycled construction materials. The main water quality analysis followed standard methods which included inflow and outflow samplings for Biochemical oxygen demand (BOD), Chemical Oxygen Demand (COD), nitrates, ammonium (Commenter, 2018), turbidity and the colour which addresses the potential for stormwater recycling and reuse for non-potable uses (irrigation in golf courses, cricket, and football stadium etc.). A hanna turbidity reader was used to measure the turbidity levels. A Hach DR 1900 spectrophotometer and a Hack LT 200 photometer was used to measure Nitrates, ammonium, and COD (Real Tech Inc., 2017). The BOD (Biochemical oxygen demand) test is carried out to measure the amount of dissolved oxygen in certain samples of stormwater. The high result of BOD means that there are smaller volumes of oxygen in the measured sample (Ysi.com, 2017).

3. Results and Discussion

Axial load testing was carried out on all four pavement rigs to withstand the similar loading conditions to a car park, which varies from small domestic driveways to car-parking facilities at supermarkets or shopping centres. The rigs which consisted of > 60 % recycled aggregates and approximately 10 % carbon-negative aggregates were tested to evaluate a load of 12.4 kN per m^2. In addition, a factor of safety was calculated of 1.35 to ensure that both the porous asphalt and concrete permeable pavement blocks is beyond safe for car parking (Chauvin and Raimbault, 1989; Ferguson, 2005; Tota-Maharaj and Hills, 2023). The secondary recycled materials were used to provide the strength needed to the drainage level as required for the stormwater to pass between the aggregates. The permeability rate of both the porous asphalt and concrete permeable pavements was not affected by the loads that were imposed due to the axial loading phase test. As the water was discharging freely without any retention. Figure 5(a) shows the axial load testing for interlocking concrete block permeable pavements and Figure 5(b) for low-carbon porous asphalt systems, respectively.


(a) (b)

Figure 5. (a) Axial Load Testing for Interlocking Concrete Block Permeable Pavements and (b) Axial Load Testing for Low-Carbon Porous Asphalt Systems at the University of Greenwich, Medway Campus, England, UK (Period of Analysis 2016-2018).

According to the axial loading calculated for the concrete block system, it was designed to fit for pedestrians' usage. As the structural sections of the sub-base materials were designed and placed without the aid of any hydraulically bounded aggregates that give the ultimate strength for high loadings. The sub-base strength can be enhanced for heavier purposes using bigger cross-section. The permeability rate when placing 12.22 kN/m^2 of uniform load with the additional safety factor of 1.35 for imposed load was not greatly affected. There were some minor effects in water discharging as the water took more time to fully drain from the rig when the load was imposed.

Table 3 shows that the rate of the ammonium, nitrate, colour, COD and BOD have decreased significantly compared to the influent stormwater water they were infiltrated by the low-carbon permeable pavement system as well as the Low-Carbon-Porous Asphalt Pavement (LC-PAP) system. This is due to the structure distribution of the aggregates and the presence of the geotextile layer. As the stormwater was forced to infiltrate between small sections in the asphalt layer and the top layers of the sub-base, most of the pollutants were prevented from passing through and were kept at the top levels of the pavement system.

As the second top layer was mix of different sizes of aggregates varying from 5 mm to 20 mm to water was enabled to discharge and all the pollutants were restricted. This can provide a wide focus on the new structure that

Table 3. Mean Stormwater Treatment Efficacies from Permeable Pavements

Stormwater Testing Parameters	Stormwater Inflow	Low-Carbon-Porous Asphalt Pavement one (LC-PAP)-1 Outflow	Low-Carbon-Porous Asphalt Pavement two (LC-PAP)-2 Outflow	Carbon-Negative Interlocking Concrete Block Permeable Pavements system one (CN-ICB-PPS)-1 Outflow	Carbon-Negative Interlocking Concrete Block Permeable Pavements system two (CN-ICB-PPS)-2 Outflow
Nitrate (mg/l)	0.878	0.133	0.315	0.171	0.210
Ammonium (mg/l)	70.1	15.2	26.2	48.5	50.3
Turbidity (FTU)	67.7	1.03	7.8	7.7	8.4
Colour (PCU)	501	5.0	14.1	8.3	8.9
COD (mg/l)	98.7	43.92	18.58	21.33	17.31
BOD (mg/l)	3.2	0.0	6.0	0.9	1.7

has been designed for the asphalt system and its effect in preventing the pollutants to pass through the draining pipes. The results of the BOD in the asphalt system are highly appreciated as the amount of the dissolved oxygen has turned down from 3.2 to 0. This result indicates that the nitrates and phosphates in the water has dropped due to the high infiltration rates produced by the system. However, the rate of the turbidity has increased after it the water was drained through the asphalt system. This can be result of the first recycled materials used in the sub-base layer, as it is made from some construction wastes as crushed concretes. The crushed concrete still has some cement powders that cause the increase in the vagueness of water which directly increases the turbidity.

Looking at the stormwater quality and performance of the concrete block pavement system, the percentage of ammonium, nitrates and colour were relatively higher than the asphalt system. That is a result of bigger gaps between the blocks and more recycled materials were placed above the saturation level which might allow some pollutants that are embedded in them to pass. These factors gave the pollutants some room to pass to the drainage pipe. Furthermore, the low-carbon and carbon negative aggregates within the permeable pavement system gave the best infiltration results when compared with the previous permeable pavements built using traditional designs with pure virgin aggregates. The Low-Carbon permeable pavements and porous asphalt are using alternative aggregates and different sequence of them which has enhanced the infiltration rates.

4. Conclusion and Future Work

Because of climate change, it is predicted that some countries will face higher rainfall events and wetted winters, while others may experience drier and drought like conditions (Evans et al, 2008; Clark, 2017). The SuDS employed in this study aimed to be mutually beneficial of reducing contamination of stormwater runoff through treatment processes and employing a greener drainage infrastructure using embedded or trapped carbon within it. These systems operated in a fashion similar to that of natural drainage systems, with a method of eliminating various forms of waste, to be environmentally friendlier and provide cleaner surroundings to communities (Wilson et al. 2004). The carbon-negative interlocking concrete block permeable pavement systems (CN-ICB-PPS) and the Low-Carbon-Porous Asphalt Pavements (LC-PAP) represent a novel green infrastructure for paving hard surfaces that can change the transportation sector across the world. The structural design covered concrete blocks and asphalt pavements. LC-PAP and CN-ICB-PPS CN-PPS has achieved two main goals, designing carbon negative system that can withstand the same axial loading as the previous traditional pavements. Moreover, enhancing the water quality by the water purification process through the infiltration between its sublayers.

Sustainability for urban cities became more concern after the new planning that is increasing on daily basis. The rainfall causes major problems to most industrial and capital cities. All the runoff that is caused by the water carries pollutants and contaminations that affects the surrounding water courses. After SuDS became familiar by time, more studies have been conducted to provide sustainable methods to eliminate the runoff without harming the ecology of the city and many new techniques have been introduced to solve this problem. The permeable pavements were one of the strategies in SuDS to collect the stormwater and infiltrate it to improve its quality of stormwater and reuse it again. LC-PAP and CN-ICB-PPS has achieved the same permeability results using a combination of virgin aggregates, recycled aggregates, and carbon negative aggregates for both the concrete block system and the asphalt system. In addition, LC-PAP and CN-ICB-PPS have demonstrated higher water infiltration than the previous permeable systems because of sub-base structural design that is used. For the LC-PAP asphalt system, the ammonium, nitrate, colour, BOD and COD have decreased significantly compared to the water from river Medway when they were infiltrated by CNPPS other than the previous system. That was attained when by designing the top layers with very tight spacing between them to ensure that the water discharges and the pollutants are restricted.

The concrete block system had a noticed decrease in the ammonium, nitrates, and colour. The results were less good than the asphalt system as the gaps between the blocks were bigger also because more recycled materials were placed above the saturation level which might allow some pollutants that are embedded in them to pass. These factors gave the pollutants some room to pass to the drainage pipe. CN-ICB-PPS designs were able to achieve the needed strength for the two desired areas of testing with cheaper cost as the recycled materials and the carbon negative aggregates forms together approximately 70% of the sub-base layer. This would give CN-ICB-PPS designs edge in the future. CN-ICB-PPS' CNPPS can have some major future works to ensure higher efficiency regarding axial loadings and bearing capacity, hydrology, and water purification.

Axial loading and bearing capacity tests should be conducted at the Transport Research Laboratory (TRL) to get the CN-ICB-PPS approved and adopted in the British Standards codes. It is essential to conduct these tests to give the opportunity for this sustainable and eco-friendly design the chance to be approved by all the city councils in the future. This study showed that carbon negative permeable pavements and low-carbon porous asphalts are economical, practical, and environmentally friendly. The world is adopting a direction of new sustainable, zero and carbon negative techniques to benefit the world and reduce the Global warming.

Unlike the rural areas, the urban cities are facing high levels of carbon dioxide. A stronger plan to reduce CO_2 emissions needs to be acted upon quickly. More work from an engineering hydrology and hydraulics perspective must be carried out for example looking at increased simulated rainfall events, stormwater flowrates mimicking transient to turbulent conditions. These simulated storm events can be conducted with different slopes to record the flow rate discharge versus time. Additional water engineering tests should be conducted, modelling different weather conditions to understand how various weathers patterns can affect the permeability levels. The engineering hydrology test will allow better understanding of soil characteristics that is used in the sub-base. In addition, it will examine the permeability of the recycled materials and the carbon negative aggregates under serious rainfall events. Future work can include detailed analysis of phosphates, turbidity and colour of the water samples influent and effluent, using additional stormwater samples from various sources to investigate the performance and pollutant removal efficacies.

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Authors' Biographical Notes:

Kiran Tota-Maharaj *is Professor of Water Resources Management and Infrastructure at the Royal Agricultural University (RAU). He arrives with a rich academic background, having previously served as an Associate Dean (External Engagement) and Reader in Water and Environmental Engineering at Aston University Birmingham, and formerly the Head of Civil and Environmental Engineering at University of the West of England Bristol (UWE Bristol). Professor Tota-Maharaj is presently the Technical Director for Water, Wastewater and Environmental Engineering at the Water Research Centre (WRc Group), Swindon, England, UK, leading on collaborative research, practice, and education between RAU and WRc. His expertise and leadership have gained recognition as a prominent engineer and practitioner within the water resources management community throughout the Caribbean, as well as the UK. Professor Tota-Maharaj's research focuses on innovative solutions for sustainable water resource management, integration of clean energy/renewable energy and environmental engineering principles in a circular economy.*

Colin Douglas Hills *is Professor and Chair of Environment and Materials Engineering and Director of the Centre for Contaminated Land Remediation at the University of Greenwich. He studied Geology (BSc) and Industrial Petrology (MSc) at Queen Mary, University of London, the UK. His PhD (Imperial College) in environmental engineering followed a period working as a field geologist in the Middle East and West Africa (Stanger, Intersite, Nigeria Dredging and Marine), and in process technology and engineering for Redland (now Lafarge). Professor Hills has received several national prizes, including the IChemE Green Chemical Technology Award, the national Shell Springboard prize, and the Times HE Award for his outstanding contribution to Innovation and Technology. His work on the beneficial re-use of waste* CO_2 *gas in the treatment (by carbonation) of contaminated soil and waste has resulted in the first commercial production of artificial aggregates. The aggregates were awarded the UK's Best Recycled Product for 2013 and are used in the world's first ever carbon negative building blocks, manufactured by Ligancite in Suffolk. Professor Hills is a founding director of both Carbon8 Systems and Carbon8 Aggregates, spin-out companies of the University of Greenwich, England, UK.*

Hazi Mohammad Azamathulla *is Professor of Civil and Environmental Engineering at the University of the West Indies at St. Augustine, Trinidad. He has a degree in Civil Engineering from SKD University (India), an Master's degree in Water Resources from Devi Ahilya University (India) and a Doctorate in Hydraulic engineering from Indian Institute of Technology, Bombay. His research interests and activities are in the fields of physical hydraulic model studies and hydro informatics. He is/has been a member of the editorial board of several high ranked Journals: Water Science and Technology, Water Science and Technology: Water Supply, Journal of Pipeline Systems Engineering – ASCE (2009-2013), Dam Engineering Journal. He is the Associate Editor of journal of hydrology (Elsevier).*

Blessing Oluwaseun Adeleke *is an experienced Chartered Engineer (CEng) and a member of the Institution of Civil Engineers (MICE) with several years of professional engineering practice. He graduated with a BSc (Hons), MSc and PhD in Civil Engineering from the University of South Wales, a PGCert in Education from the University of Essex and a Fellow of Higher education (FHEA). Currently, Dr. Adeleke is a Senior Lecturer in Civil Engineering at the University of South Wales, UK, where he is actively involved in undergraduate teaching, postgraduate teaching, and PhD supervision. His research interests include construction materials, civil engineering materials, structural analysis, soil-structure interaction, Finite Element Modelling, Concrete Material Technology and Construction Engineering.*

Ghassan Nounu *is a Senior Lecturer in Structural Engineering and programme leader of the MSc civil engineering at the University of the West of England, Bristol, UK. He specialises in structural analysis and design and construction materials. His research expertise is on sustainable construction materials in reinforced concrete. Dr. Nounu published work on the shear strength of reinforced concrete, reinforced concrete repairs and finite elements modelling of reinforced concrete. His research expertise addresses non-destructive testing of reinforced concrete especially with impact-echo testing technique. Dr. Nounu has supervised several PhDs and was an external and internal examiner of several civil engineering postgraduate and research students. He is a qualified external examiner of MSc and MEng/BEng programmes at two universities in the UK.* ■