Novel permeable pavement systems utilising carbon-negative aggregate

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ABSTRACT: The use of commercially produced Carbon-Negative aggregates from Carbon8 (a British company which applies patented Accelerated Carbonation Technology (ACT) to solidify waste residues producing useful eco-friendly aggregates) is being investigated in the Caribbean islands of Trinidad, Tobago and St. Lucia. Typical construction of the subbase layer of pavements in the Caribbean include layers of virgin aggregate material (gravel, pea gravel) on which the base course layer is located. These materials are usually unbound granular (crushed stone, crushed slag, crushed concrete, slate) or cement-bound. Permeable Pavement Systems (PPS) have emerged over the years using various quality of subbase materials including large pieces of rocks and concrete. For the first time in the Caribbean, the design, construction and implementation of such pavement systems is being carried out. The novel pavement systems consist of permeable or pervious concrete paving blocks and the Carbon-Negative aggregates in the sub-base as an innovative and effective method of providing structural pavements, whilst allowing urban stormwater runoff to infiltrate naturally into the pavements (mimicking the hydrologic cycle) into the base/sub-base reservoir for urban runoff attenuation and an overall reduction in stormwater discharge. These pavement systems are being considered to reduce the overall carbon footprint on the construction and implementation phase of pavements, in addition to reducing surface water flooding in several towns and cities across these Caribbean Small Island Developing States (SIDS). The project includes ongoing experimental assessment of the Permeable Pavement Systems (PPS) using Carbon-Negative aggregates versus conventional pervious pavements from a water quality, structural integrity and hydraulic perspective. Stormwater is being collected from various towns and cities across the islands and applied uniformly over the pilot scaled permeable pavements using a rainfall simulator. The permeable pavements stormwater treatment efficacies are being evaluated for the removal and retention of nutrients (total nitrogen and total phosphorus), heavy metals (zinc, lead, copper, cadmium), suspended solids and turbidity. The hydraulic performance, flow through and clogging patterns of these pavements are also being measured over a simulated 10-year period of sediment loading. Load bearing and deflection test are being carried out on the various pavement designs to assess its structural integrity and load bearing capacity. Static and dynamic loads applied representing the maximum contact pressure varying from 0.03 to 1.7 MPa over the cross-sectional area of 0.2 m^2 (permeable pavement surface area). These contract pressures represent various loads from heavy vehicles, cars, pallets and handling equipment of industrial areas (ports).

1. INTRODUCTION

Preserving the environment and conserving the rapidly diminishing natural resources should be the core of sustainabl. Development.[1] With the goal of promoting the sustainable use of natural materials, several countries, regions, and municipalities are accelerating their efforts towards formulating policies that promote the wide-scale recycling of waste. products.[2] A wide variety of wastes usable include fly ash, bottom ash and flue gas scrubber sludge from combustion processes, sewage sludge, slags from the metallurgical industry, municipal refuse and demolition wastes.[3] Advancement in infrastructural development provides significant opportunities for the use of waste and recycled materials encouraging reduced waste disposal at landfills and/or environmental costs.[2,4,5]

The average waste per capita generation rate in the Caribbean is 1.3 kg/capita/day with an astounding 83% of the waste landfilled.[6] The use of recycled waste materials in permeable pavements will be beneficial both economically and environmentally through reductions in the volume of material landfilled as well as the rate of consumption of landfill space. Ultimately, this will lead to a reduction is the usage of natural aggregates, significantly reduce the carbon foot prints as compared to using traditional quarried materials and finally lead to a more sustainable environment.[7] This is particularly important to Caribbean Small Island Developing States (SIDS) as the effects of improperly disposed waste are often amplified through indirect contamination of surface and groundwater, degradation of coastal and marine resources such as wetlands, and coral reefs, limited land space for housing disposal facilities and insufficient resources for regulating and managing waste.[8]

Recycling of waste materials into sustainable geotechnical applications is of paramount importance. Innovative ways of conversation of natural resources and reduction of the volume of material landfilled are sought worldwide.[9] The sustainable use of recycled waste materials in civil engineering applications have immense social and economic benefits to both industrialized and developing nations.[10] An attempt was therefore made in this paper to examine the performance (hydraulic and pollutant removal efficiency) of permeable pavement systems through a novel approach utilizes carbon negative aggregates (hereinafter referred to as C8 Aggregates) from Carbon8 Aggregates Limited (a British company which applies patented accelerated carbonation technology (ACT) to solidify waste residues producing useful eco-friendly aggregates) in the sub-base of a permeable pavement. Unfortunately, the authors of this paper were unable to secure a shipment of C8 Aggregates from the United Kingdom to Trinidad and Tobago within sufficient time so as to present relevant results in this paper. As such, the authors of this paper have sought to give a brief description of C8 Aggregates coupled with a description of ongoing and proposed methodologies with regards to the use of recycled waste materials in permeable pavements. At this point readers are asked to note that the relevant experimental tests are ongoing with limited results being report on.

1.1 *Background*

Carbon8 Aggregates Limited from the U.K. has indeed made strives to recycle municipal solid waste into a suitable construction material, C8 Aggregate. These aggregates are lightweight aggregates manufactured from Accelerated Carbonation Technology (ACT). The technology utilizes waste carbon dioxide to pelletise Municipal Solid Waste Incinerator (MSWI) ash into potential aggregates for construction. The accelerated carbonation process captures more carbon dioxide from the waste than is used during plant processing. Hence the development of a "carbon negative" aggregate as per laboratory-based calculations. The solidified product contains permanently bound carbon dioxide gas.[11] The raw materials used for this production are thermal residues for example fly ash and Air Pollution Control residue (APCr) from waste to energy plants. The C8 Aggregates are grey sub-rounded, homogeneous, and with a rough surface. Typical applications of C8 Aggregate include concrete construction blocks, concrete and floor screeds as shown in Figure 1.[11,12] Various properties of C8 Aggregates are listed in Table 1.

Table 1. Properties of C8 Aggregate

Property	Value	Reference
Particle size (mm)	4–16	
Dry loose bulk density (kg/m^3)	950–1100	EN 1097
Particle density (kg/m^3)	1.94	EN 1097
Crushing resistance (N/mm^2)	6.6 (typical) 5.2 (min)	EN 13055
Moisture content as delivered (%)	8 (typical)	EN 13055
Water absorption (%)	18.8	EN 1097
Water soluble chloride (%)	4.2	EN 1744
Water soluble sulfate (%)	0.1	EN 1744
Total sulfate (as SO_3) (%)	1.78	EN 1744
LA Abrasion (%)	39	EN 1097
Magnesium sulphate soundness (%)	30.1	EN 1097
Drying shrinkage (%)	0.021	EN 1367

Source: Carey, *et al*.[12]

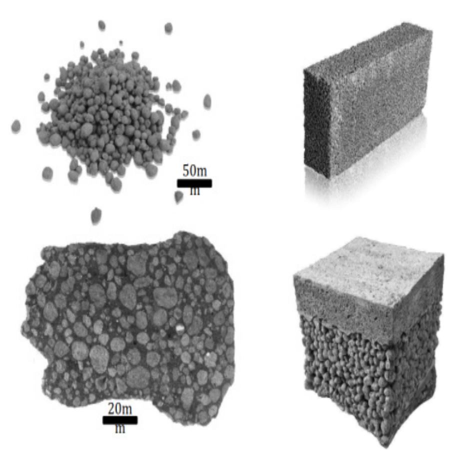


Fig. 1. Applications of C8 Aggregate;
top left – C8 Aggregate, top right - concrete block,
bottom left – cross section of readymix concrete,
bottom right – section of screed floor.

Source: Carey, *et al*.[12]

Incineration is an efficient way to reduce the volume of waste and demand for landfill space.[13] It involves the burning of generated MSW at very high temperatures. Through incineration, it is possible to recover energy by 70% and reduce the mass and volume of waste by 90%.[14] Incineration is however, a highly complex technology that requires large capital investments, high operating costs, skilled per sonnel and careful maintenance.[15] According to The World Bank,[15] these high costs have made MSWI beyond the reach of lesser developing countries. In 2007, there were 13 incinerators in the UK with a total processing capacity of 2.9 million tons per year.[14] Comparatively, very little incinerators are currently operating on a relatively small scale in the Caribbean–1 in the British Virgin Islands (U.K Colony) and 2 in Barbados.[6]

Kinnaman[6] argues however, that incineration may not be appropriate for several Caribbean countries for two main reasons. Firstly, MSW in these SIDS are not very combustible due to a large percentage of organic waste streams which contain low levels of energy and high levels of moisture content. Interestingly however, Trinidad and Tobago, one of the more developed states across the Caribbean recorded only 27% organics[16] in their waste characterization study conducted in 2010 as shown in Figure 2. Secondly, Kinnaman[6] mentions economies of scales in incineration whereby it becomes uneconomical for plants to operate at less than 1,100 tons of waste per day. Indeed, Kinnaman[6] suggested that Trinidad and Tobago was able to capture these scale economies due to its large population.

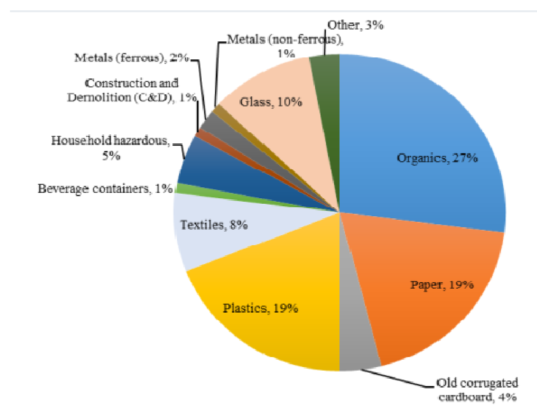


Fig. 2. Solid waste characterisation for Trinidad and Tobago, 2010.

Source:[16]

Permeable Pavement Engineering (PPE) dates back to the early 1970s.[17] It involves an effective and simple method of providing structural pavements, whilst allowing runoff to infiltrate freely through the pavement surfaces and into a base/sub-base reservoir.[18,19]

Permeable Pavements (PP) are one form of Sustainable Urban Drainage Systems (SUDS) or Low Impact Development (LID) practises which offer a viable solution to mitigate urban runoff within Caribbean SIDS.[20] PP supersede conventional paving surfaces with an at-source control to prevent or significantly delay stormwater runoff generation.[21] The primary objecttives of PPS are to reduce surface runoff quantities and peak flows; increase groundwater recharge; improve stormwater runoff quality and reduce pollution of natural watercourses.[22] Traditionally, permeable pavements have been utilised for light weight pavement use due to inferior structural capacity and geotechnical design considerations. Typical applications include roadway shoulders, residential driveways, parking lots and pedestrian access.[23]

Permeable pavements have different objectives and design requirements to conventional pavements.[24] Conventional pavements designed for use by vehicular traffic typically consist of a surface seal and one or more compacted aggregate subbase/base courses overlying a compacted subgrade.[24] The typical design of conventional pavements restricts the entry of stormwater into the pavement structure via a surface seal. PP on the contrary, allow the infiltration of water through the pavement structure[25] and therefore mimics the natural soil environment. A typical schematic layout of a PPS is shown in Figure 3. The typical structure consists of a permeable paving surface and layers of coarse aggregate materials that function as a storage reservoir during rainfall events. Aggregates such as crushed stone are the most dominant component in the PPS. For improved hydraulic and structural performance these aggregates are typically clean, single-sized or open-graded and angular. The open voids between particles allow extremely high permeability usually in excess of 25 m/h.[26]

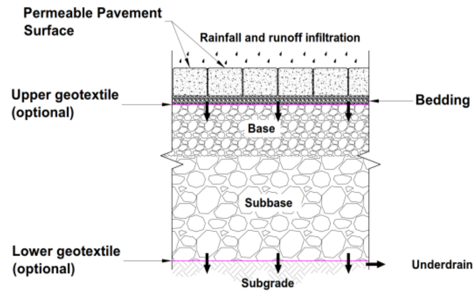


Fig. 3. Schematic diagram of a typical permeable pavement vertical profile.
Adapted from:[27]

Permeable pavements are usually designed with varying boundary conditions for full, partial or no infiltration.[18] When infiltration into the native soil is not desired, an impermeable geo-membrane layer is often placed between the existing subgrade and the course aggregate material along with the installation of an underdrain (perforated pipe) positioned at or near the base of the aggregate reservoir. This underdrain pipe collects and conveys runoff to a desired outfall. This is often the case for permeable pavements installed over clayey subgrade soils with high shrink-swell potential and low permeability. These pavements are typically designed with a thicker aggregate storage layer for increased structural capacity.[28]

PPS hydraulic characteristics contribute to four areas of hydrologic control: peak flow, volume, hydrograph timing, and duration.[21] Results comparing the hydrologic performance of permeable pavements are not only dependent on the local climatic and geological conditions but also differences in design of the pavement structure particularly boundary drainage conditions in addition to the age of the pavement. Other conditions such as rainfall events of varying magnitude, intensity and duration, and different antecedent and seasonally-variable conditions must be monitored to ensure full characterisation of the hydrologic behaviour of a permeable pavement. Spatial heterogeneity is typical for field-scale installations due to differential inputs, traffic loadings, drainage patterns and installation and maintenance conditions across the pavement surface.

Research studies often use an impervious pavement, typically traditional hot mix asphalt as a control over which the hydrologic performance of a permeable pavement in terms of outflow volume, rate, timing and frequency is typically measured and reported against.[29] Numerous researchers have reported on the use of permeable pavements as an effective tool in stormwater management promoting reduced runoff quantity and peak runoff rates, and delay peak flows.[30–35]

Stormwater runoff from urban areas generally tends to carry various pollutants which have previously been deposited onto impermeable surfaces from a wide variety of anthropogenic activities and environmental processes.[29] These include suspended solids, oils, heavy metals, organic matter, bacteria and nutrients that originate from varying sources including decomposing litter, building materials, vehicle wear and traffic emissions.[36] Left untreated, the quality of nearby watercourses and the environment in general is at risk. Permeable pavements have been shown to reduce stormwater pollutants including heavy metals, motor-oil, sediments and some nutrients.[30–32,37–40] Permeable pavements have also been shown to be efficient attenuators for bacteria such as E. coli and faecal Streptococci.[41]

In terms of stormwater management, surface clogging has been reported as the primary failure mechanism of permeable pavements.[21] Clogging reduces the hydraulic performance of a permeable pavement whereby maintenance operations are required to restore performance.[42] Numerous researchers have shown an exponential decay of surface infiltration rate as a function of age of the permeable pavement.[43–45] Emerson, *et al*.[46] reported that infiltration rates with permeable pavers reduced by one to two orders of magnitude after three years of operation. Borgwardt[47] reported that the infiltration performance of permeable pavements decreases in the order of the power of ten after a few years of operation. Numerous researchers have cited periodic maintenance as being fundamental to limiting clogging of PPS.[24,42,48–50] Examples of maintenance techniques include manual removal of the upper 20 mm of fill material, mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high pressure washing, and milling of porous asphalt.[45,51]

Despite the widely reported use of PPS, very few studies have reported on the use of recycled waste materials as a sustainable construction material in permeable pavements. Rahman, *et al*.[22] investigated through a laboratory study, the impact of recycled construction and demolition (C&D) materials; Crushed Brick (CB), Recycledconcrete Aggregate (RCA) and Reclaimed Asphalt Pavement (RAP) on the geotechnical and hydraulic performance of a permeable pavement system. Rahman, *et al*.[22] concluded that the C&D materials were suitable alternative ûlter materials in PPS.

2. EXPERIMENTAL METHODS AND MATERIALS

2.1 *Experimental apparatus*

Three 450 mm (18 in.) × 420 mm (16.5 in.) × 610 mm (2 ft.) pavement rigs were constructed from 19 mm (3/4 in.) construction plywood. These rigs were made watertight by inserting a 3 mm thick layer of commercially available PVC based ‘pond liner’ on the inside. PVC solvent was used to ‘glue’ five cut sheets of liner together to match the interior dimensions of the rigs. Three outflow 12.5 mm (1/2 in.) PVC pipes were installed on one side of each rig at varying heads of 50 mm (2 in.), 250 mm (10 in.) and 480 mm (19 in.) above the base of the rigs. All drain pipes were attached via a 19 mm (3/4 in.) PVC pipe bulk headfitting installed through drilled 44 mm (1.75 in.) holes. The materials were purchased from local hardware stores in Trinidad and Tobago. Three rigsand a schematic of one rig after constructionare shown in Figures 4 and 5 respectively.

Fig. 4. Completed pavement plywood rigs.

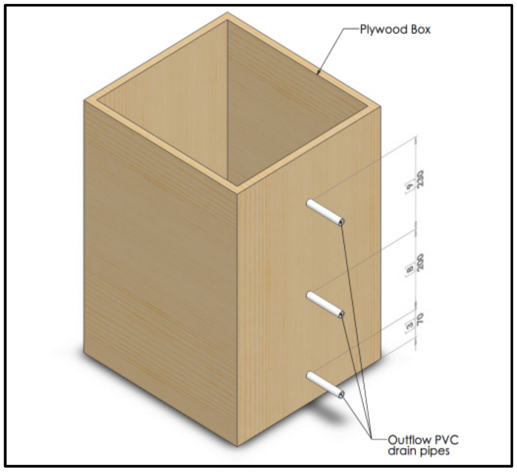


Fig. 5. Schematic of constructed plywood rig.

Attempts were made to replicate natural rainfall conditions using a purpose built rainfall simulator. Numerous studies have successfully used rainfall simulation techniques in their research methodologies.[24,34,35,52–57] The rainfall simulator was constructed of 12.5 mm (1/2 in.) PVC pipes and fittings. It consisted of outer frame measuring 610 mm (2 ft.) × 610 mm (2 ft.) × 1.5 m (6 ft.) along with an inner ring which matched the dimensions of the rig (450 mm × 420 mm). This inner ring was surrounded by a clear sheet of plastic whose purpose was to prevent any loss of simulated rainfall. At the top of the PVC frame were six 12.5 mm (1/2 in.) horizontal PVC pipes (parallel to the surface of the rigs) and spaced 60 mm (2.5 in.) from each other. To facilitate rainfall simulation, a series of 3 mm diameter holes spaced at 50 mm apart were drilled into the underside of these pipes. Water was supplied to the system via a 12.5 mm (1/2 in.) hose connected to a submersible pump within a water infilled plastic container. A valve and flowmeter (Gardena® water meter purchased from Amazon®) were used to control the flow of water to the system. The flowmeter was capable of measuring total volume (l) and flowrate (l/min). Attempts at visually simulating droplets were made by allowing the jets of water flowing from the perforated PVC pipes to pass through two horizontal insect screen wire mesh sheets placed 300 mm (12 in.) below the drilled holes prior to hitting the pavement surface.Water exited the pavement via outflow pipes as described previously and collected in a plastic container. Outflow (at desired heads) was measured via another Gardena® flowmeter. A schematic and actual layout of the experimental rig set up are shown in Figures 6 and 7.

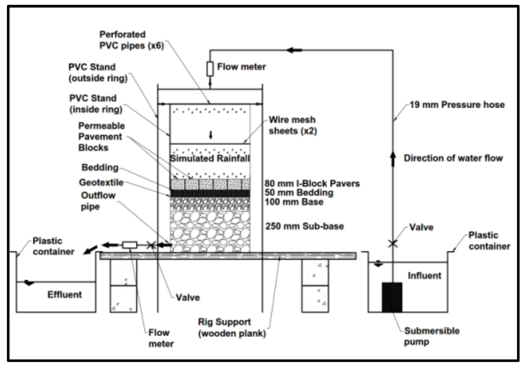


Fig. 6. Schematic of permeable pavement laboratory set up.

Fig. 7. Layout of permeable pavement laboratory rigs.

The permeable pavements were designed in accordance with technical guidance from previous researchers.[23,55,58,59] Moreover, numerous institutions worldwide have provided general guidance relating to the design and construction of permeable pavements. In the U.K., British Standard BS 7533–13[60] offers guidance on the design of permeable pavements. Likewise, the Interlocking Concrete Pavement Institute[61] has also provided industry guidance for Permeable Interlocking Concrete Pavement (PICP) in the U.S.A. and Canada. Similarly, in Australia, the

Concrete Masonry Association of Australia (CMAA) has made available freely on their website[62] several design guidance manuals on permeable paving. Each of these standards provide similar recommendations relating to site boundary conditions, pavement structure (layer thickness, aggregate gradations) pavement usage and so on. Nevertheless, the use of permeable pavements as a stormwater management option is novel to the Small Island Developing States (SIDS) across the Caribbean. Consequently, only certain recommendations from these industry guidelines along with previous studies particularly relating to aggregate gradations and pavement layer thicknesses were considered in this research.

The permeable pavement comprised of an 80 mm (3.2 in.) I-Paver block, a 50 mm (2 in.) bedding layer, a geotextile layer, 100 mm (4 in.) base course and a 250 mm (10 in.) sub-base layer. The pavement structure is illustrated in Figure 8. A waterproof wooden ruler (5 mm division) was secured along one of the inside faces of each rig. This allowed for infiltration test measurements and potential settlement measurements.

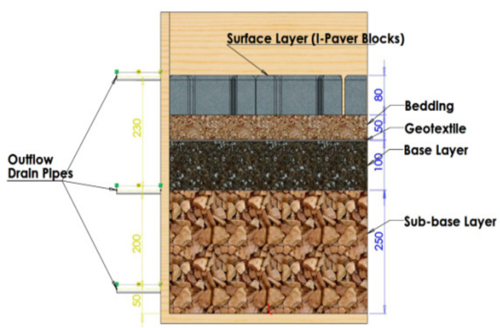
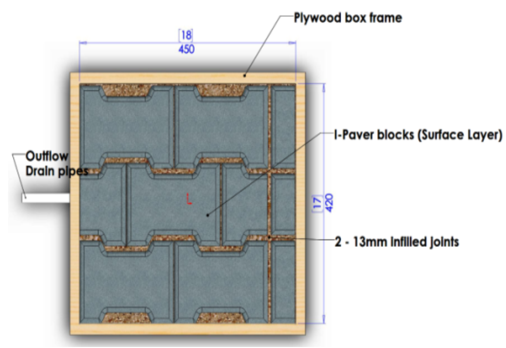


Fig. 8. Permeable pavement structure and cross section.

The I-Paver blocks were purchased from concrete block manufacturer in Trinidad and Tobago, called Abel Building Solutions.[63] According to its website, these I-Paver blocks meet the American Standard for Testing and Materials (ASTM) C936, standard specification for solid concrete interlocking paving units.[64] Each block unit measures 80 mm (3.2 in.) × 197 mm (7.9 in.) × 143 mm (5.7 in.) and weighs 4.35 kg (9.7 lbs). Typically, the paver blocks are designed for and installed in Trinidad and Tobago with little to no gaps. However, the authors have made a modification by increasing the width of the gaps (up to 13 mm) to allow for increased infiltration of stormwater to the underlying pavement filter layers (Figure 9).

(a)



(b)

Fig. 9. Plan view of installed I-paver blocks; (a) Typical installation with I-pavers and wide gaps (b) Schematic.

The bedding layer comprised of 5 mm (sieve no. 4) ASTM No. 8 washed aggregate. The base course layer was formed of 12.5 mm (1/2 in. sieve) ASTM No. 57 washed aggregated. The sub-base layer comprised of 19 mm (3/4 in. sieve) ASTM No. 5 aggregate. Sieve analysis as per ASTM C136[65] was used to verify the Particle Size Distributions (PSD). The sub-base materials varied for each rig. Rig 1 comprised of basalt from St. Lucia, rig 2 comprised of limestone from Trinidad and Tobago and rig 3 comprised of crushed Recycled Concrete Aggregate (RCA). The RCA was obtained by crushing several concrete cylinders at the Department of Civil and Environmental Engineering of the University of the West Indies, St. Augustine Campus in Trinidad and Tobago (DCEEUWITT) concrete/ soils laboratory. A sample of the various types of aggregates usedin the experimental permeable pavement rigs is shown in Figure 10.

For all rigs, a nonwowen geotextile layer (TencateMirafi®) was placed at one location; between the bedding layer and the base course layer. The properties of this geotextile layer are presented in Table 2. Numerous researchers have reported on the ability of geotextiles to improve the short term pollutant removal efficiency[22,27] and improve infiltration and attenuation[66] of permeable pavements.

Table 2. Physical and hydraulic properties of non-woven geotextile

Property	Test method	Minimum average roll value
Mechanical properties		
Grab tensile strength (N)	ASTM D4632	912
Trapezoid tear strength (N)	ASTM D4533	356
CBR puncture strength (N)	ASTM D6241	2224
Hydraulic properties		
Apparent opening size (AOS) (mm)	ASTM D4751	0.18
Permittivity (s^{-1})	ASTM D4491	1.4
Flow rate ($l/min/m^2$)	ASTM D4491	3870
UV resistance after 500 hrs. (% strength)	ASTM D4355	70

(a)

(b) (c)

Fig. 10. Types of aggregates used in laboratory-scale rigs; (a) RCA, (b) Basalt, (c) Limestone.

2.2 *Ongoing experimental procedure*

2.2.1 Geotechnical and physical testing

A series of geotechnical and physical tests on the various aggregates was conducted at the Department of Civil and Environmental Engineering of the University of the West Indies, St. Augustine Campus in Trinidad and Tobago (DCEEUWITT) asphalt laboratory. As mentioned previously, the gradation or PSD of the various aggregate layers was conducted in accordance to ASTM C136.[65] This is presented in Figure 11. The laboratory physical and geotechnical tests listed in Table 3 were conducted on the various aggregate layers and are listed in Table 4.

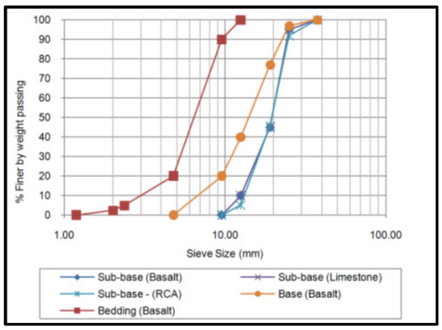


Fig. 11. Particle size distribution of aggregates used in the various pavement rigs.

Table 3. Geotechnical and physical tests conducted on aggregates

Test name	Source
Specific gravity and absorption of coarse aggregate	ASTM C127[67]
Unit weight and voids in aggregate	ASTM C29[68]
Los angeles (LA) abrasion	ASTM C131[69]
Aggregate impact value	BS 812[70]
Flakiness index	BS EN 933–3[71]
Porosity	ASTM C29[68]
pH	BS 1377[72]

2.2.2 Hydraulic conductivity and clogging pattern

The hydraulic conductivity of the test rigs was measured prior to the commencement of simulation. This gave an indication of permeability of the pavement rigs immediately after construction. The rigs were saturated with water from the mains using a pipe hose up to a predetermined head of water above the pavement blocks. The time for the water level to drop to a level just above the blocks was measured and recorded. A schematic of the details of the hydraulic testing is presented in Figure 12. The hydraulic conductivity was calculated from Darcy's law as a falling head test from (1).

$$k = \frac{L}{t} \ln \frac{h_1}{h_2} \qquad \ldots (1)$$

where k is the coefficient of permeability (mm/h), L is the length of the specimen (mm), t is the time (h), h_1 is the initial head of water above the pavement blocks and h_2 is the final head of water dropped to after time t (mm).

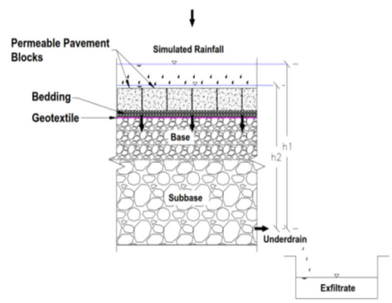


Fig. 12. Details of hydraulic conductivity testing.

The post construction infiltration rates of the test rigs are presented in Table 5. Readers are reminded that tests are ongoing with limited results forthcoming at this stage. This test shall be repeated after every simulated stormwater event. Accelerated Simulation Techniques (AST) will be used to simulate at least 10 years of stormwater obtained from various towns and cities in Trinidad and Tobago. The effective life of the pavements will be determined from an assessment of pavements infiltration rates at yearly intervals over the accelerated 10-year period. Based on a loading surface area of 0.189 m^2 and a mean annual rainfall of 2200 mm (88 in.) for Trinidad and Tobago, approximately 416 *l* of stormwater is required to simulate 1 year's volume of rainfall. Numerous researchers have used AST along with infiltration rate measurements for assessing the clogging patterns of laboratory-scale permeable pavements.[24,34,73]

Table 4. Physical and geotechnical properties of aggregates used in test rigs

Properties	Bedding - basalt	Base - Basalt	Sub-base 1 - basalt	Sub-base 2 - limestone	Sub-base 3 - RCA
ASTM grading classification	No. 8	No. 57	No. 5	No. 5	No. 5
Specific gravity, G_s (kg/m^3)	2.709	2.709	2.709	2.575	2.245
Water absorption (%)	1.2	1.2	1.2	0.8	7.1
LA abrasion (%)	18	18	18	53	44
Impact (%)	16	16	16	38	–
Flakiness index (%)	1	1	1	3	–
Bulk density (kg/m^3)	1530	1559	1541	1504	1252
SSD bulk density (kg/m^3)	1548	1578	1559	1516	1341
Voids ratio, e	0.433	0.422	0.429	0.414	0.44
Porosity, n (%)	30	30	30	29	31
pH	8.51	8.51	8.51	8.28	12.26

Table 5. Initial laboratory infiltration rates of the pavement rigs

Test no.	Date	Coefficient of permeability, *k* (mm/h)			
		Sub-base material			
		Basalt	Limestone	RCA	C8 Aggr.
1	8-12-16	2275	2459	2272	–

2.2.3 Water quality

Stormwater will be collected in plastic 20 l buckets from various towns and cities in Trinidad and Tobago during or immediately after rainfall events. The stormwater will be applied uniformly over the pavement rigs at 2.0 $l/min/m^2$ for a minimum of 10 minutes using the purpose built rainfall simulator as described previously. Throughout the simulation, the influent (raw stormwater) will be continuously stirred (manually) to ensure particles remain in suspension. Towards the completion of the rainfall application, effluent samples will be collected from the outlet of the drain pipe for analysis. The permeable pavements stormwater treatment efficacies will be evaluated for the removal and retention of nutrients (nitrates, phosphates, sulphates), heavy metals (zinc, lead, copper, manganese, iron), suspended solids, dissolved solids, total chlorine, conductivity and turbidity.

2.2.4 Hydrology

This experimental procedure will involve applying three rainfall intensities and durations with repetitions to each permeable pavement test rig. The purpose built rainfall simulator will be used to apply rainfall uniformly over the pavements. As mentioned previously, flows will be measured and controlled using valves and flowmeters (Gardena).

2.2.5 Stiffness and deflection

Stiffness, moduli of elasticity and defection of the permeable pavement test rigs will be assessed using the Portable Falling Weight Deflectometer (PFWD) shown in Figure 13. This will be conducted at the Department of Civil and Environmental Engineering of the University of the West Indies (DCEEUWITT), St. Augustine Campus in Trinidad and Tobago. The PFWD consists of a base plate with an accelerometer (sensor), a falling load device and a deflection measuring instrument. The generation of load and deflection created by a free falling weight is measured using the PFWD. The PFWD available at the DCEEUWITT consists of a 300 mm (12 in.) diameter base plate with an accelerometer, and a 10 kg drop weight at a maximum height of 720 mm (29 in.) above the base plate. A diagram of a PFWD is presented in Figure 13.

Fig. 13. PFWD at the DCEEUWITT.

3. CONCLUSION AND OUTLOOK

Numerous researchers have reported successful uses of permeable pavements worldwide. Should permeable pavements be used effectively in urban areas of the Caribbean, research is needed to validate their use as a long-term sustainable urban drainage option for flood risk reduction and improvement in urban runoff quality. On-going research at the University of Greenwich, the University of Trinidad and Tobago, the University of the West Indies, St. Augustine Campus and AECOM addresses timely and novel PPE, designs and sustainability applicable to Caribbean SIDS for low-cost, eco-friendly paving systems within the built environment.

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