Assessment of the physical characteristics and stormwater effluent quality of permeable pavement systems containing recycled materials

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Abstract

This paper evaluates the physical characteristics of two recycled materials and the pollutant removal efficiencies of four 0.2 m^2 tanked permeable pavement rigs in the laboratory, that contained either natural aggregates or these recycled materials in the sub-base. The selected recycled materials were Crushed Concrete Aggregates (CCA) and Cement-bounded Expanded Polystyrene beads (C-EPS) whilst the natural aggregates were basalt and quartzite. Natural stormwater runoff was used as influent. Effluent was collected for analysis after 7–10 mins of discharge. Influent and effluent were analysed for pH, Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Electroconductivity (EC), turbidity, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Nitrate-Nitrogen (NO_3-N), reactive phosphorous (PO_4^{3-}) and sulphates (SO_4^{2-}). Both CCA and C-EPS had suitable physical properties for use as sub-base materials in PPS. However, C-EPS is recommended for use in pavements with light to no traffic because of its relatively low compressive strength. In terms of pollutant removal efficiencies, significant differences ($p < 0.01$) were found in pH, EC, TDS, DO, PO_4^{3-} and SO_4^{2-} across all rigs whereas no significant differences ($p > 0.05$) were found with respect to TSS, turbidity, COD and NO_3-N. Effluent from rigs containing CCA and C-EPS saw significant increases in pH, EC and TDS measurements whilst improvements in DO, TSS, turbidity, COD, PO_4^{3-} and SO_4^{2-} were observed. All mean values except pH were, however, within the Maximum Permissible Levels (MPLs) of water pollutants discharged into the environment according to the Trinidad and Tobago Environmental Management Authority (EMA) or the United States Environmental Protection Agency (US EPA). In this regard, the CCA and C-EPS performed satisfactorily as sub-base materials in the permeable pavement rigs. It is noted, however, that further analysis is recommended through leaching tests on the recycled materials.

Keywords: permeable pavement; crushed concrete aggregates; pollutant removal; small island developing states (SIDS); expanded polystyrene; recycling

Introduction

Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Water Sensitive Urban Design (WSUD) or Best Management Practices (BMPs) such as Permeable Pavement Systems (PPS), offer a viable solution to the stormwater management problems experienced within most Small Island Developing States (SIDS) across the Caribbean (Parkinson 2002). Other SUDS such as detention/retention ponds and wetlands that provide vital stormwater storage, are often difficult to implement because of land/space restrictions. PPS supersede conventional paving surfaces with an at-source (i.e. where rainfall makes landfall) control to prevent or significantly delay stormwater runoff generation (Fassman and Blackbourn 2010). Documented utilisation of PPS dates back to the early 1970s (Thelen et al. 1972). PPS have been engineered as hybrid infrastructure whereby structural pavements that are traditionally designed to accommodate light traffic such as residential driveways and parking lots, also serve as stormwater containment reservoirs by providing infiltration and temporary detention of stormwater runoff (Scholz and Grabowiecki 2007, Jato-Espino et al. 2016, Rodríguez-Rojas et al. 2018). The stored water is eventually released into a receiving drainage channel or allowed to infiltrate into the subsoil (Interpave 2018, Hein 2014). Utilisation of PPS can most likely be a viable option to bridge the gap between societal competing needs of urban development and stormwater management in Caribbean SIDS through this hybrid function. The primary objectives of PPS are to reduce surface runoff quantities and peak flows; increase groundwater recharge; improve stormwater runoff quality and reduce pollution of natural watercourses (Rahman et al. 2015b, Weiss et al. 2017). In Japan, permeable pavements have been recommended as post-modern pavements for the design and development of resilient transportation infrastructure (Jamshidi et al. 2019).

The typically structure of PPS contains a permeable paving surface and layers of coarse aggregate (sub-base and base) materials that function as a storage reservoir during rainfall events; a bedding layer which supports the paving surface and optional geotextile layer(s). Aggregates such as crushed stone in the base and sub-base layers are the most dominant component. 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 (Ferguson 2005).

A variety of permeable pavements have been identified based on their surface paving material. The distinguishing factor among them is related to the total pore space, spatial arrangement of the underlying open-graded layers and structural strength. They are either monolithic, modular or grid types. Monolithic permeable pavements facilitate infiltration of water through their surfaces. Examples include porous asphalt and porous concrete. Modular pavements consist of solid permeable pavement concrete blocks placed adjacent to each other in various patterns with infiltration taking place through the joints between the blocks. The most prevalent modular units are Permeable Interlocking Concrete Pavers (PICP). In the USA, PICPs conform to ASTM C936 (ASTM International 2018a) which ensures that pavers are at least 60 mm thick with a minimum compressive strength of 55 MPa. Grid pavements consist of large gaps which facilitate infiltration. Examples include concrete grid pavers and plastic grid pavers (Collins 2007).

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 (Drake et al. 2014a). 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 (Scholz 2013). Left untreated, the quality of nearby watercourses and the environment in general are at risk. Permeable pavements have been shown to reduce stormwater pollutants including heavy metals, motor-oil, sediments and some nutrients (Pratt et al. 1995, Brattebo and Booth 2003, Bean et al. 2007, Li et al. 2017, Sounthararajah et al. 2017, Abdollahian et al. 2018, Holmes et al. 2017, Kim et al. 2017). However, the nutrient removal capabilities of permeable pavements are less understood (Collins and Hunt 2008) with some studies (Day et al. 1981, Bean et al. 2007, Gilbert and Clausen 2006, Collins et al. 2008) reporting varying results. Day et al. (1981); Bean et al. (2007) and Gilbert and Clausen (2006) reported removal of total phosphorous (TP) attributed to adsorption by sand and gravel sub-base materials whilst a similar study (Collins et al. 2008) has reported little change in TP concentrations. A handful of studies (Pagotto et al. 2000, Gilbert and Clausen 2006) have shown a reduction in concentrations of all measured nitrogen species (NH_4-N, TKN and NO_3-N) whereas other studies (Day et al. 1981, Collins et al. 2008) have reported certain forms of nitrogen concentrations to rise or remain unchanged. These differences could be attributed to varying local environmental conditions in addition to design and maintenance needs. Permeable pavements have also been shown to be efficient attenuators for bacteria such as *E. coli* and faecal Streptococci (Tota-Maharaj and Scholz 2010).

Permeable pavements have been given credit for entrapping sediments and adsorbing other pollutants during infiltration of stormwater runoff (Brattebo and Booth 2003, Bean et al. 2007, Collins 2007, Beecham et al. 2012, Charlesworth et al. 2017). This process has, however, been shown to result in clogging of the passages within the mass of filter material forming the pavement, resulting in reduced hydraulic conductivity (Pratt et al. 1995, Borgwardt 2006, Siriwardene et al. 2007, Lucke and Beecham 2011). Hence, permeable pavements, as with all filtration systems, will, over time, require removal of entrapped particulate matter (Sansalone et al. 2012).

Sustainable development promotes environmental preservation and conservation of the rapidly diminishing supply and availability of natural resources (Rao et al. 2007). The typical design of permeable pavements requires a significant volume of construction aggregates; significantly greater than that required in conventional roadway pavements. Such large quantities may not always be available in a timely manner and impose added stress on natural resources and the environment. 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 (Inyang 2003). 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 (Inyang 2003, Chang et al. 1999, Cheeseman et al. 2005).

Most Caribbean SIDS such as Trinidad and St. Lucia are geologically confined, thus limiting the availability of sufficient natural aggregates for construction. Moreover, there is a growing demand for construction aggregates in SIDS as demand for housing and other public infrastructure increases with urbanisation, population growth and tourism (McHardy and Donovan 2016, IDB 2018, Monrose and Tota-Maharaj 2018). In Trinidad and Tobago for instance, the demand from the construction industry has seen a drastic increase during the past decade (Lalla and Mwasha 2014). However, in more recent times, the fluctuating prices of oil and natural gas which represents 35% of the Gross Domestic Product (GDP) of Trinidad and Tobago (GoRTT 2018), has since resulted in a decline in construction activity. Nevertheless, the demand for civil engineering materials, construction aggregates in particular remain high (Lalla and Mwasha 2014). The use of recycled waste materials in permeable pavements will, therefore, be beneficial both economically and environmentally, through reductions in the volume of material landfilled as well as the demand for landfill space. Ultimately, this will lead to a reduction in 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 (Tam 2009).

Recycled waste materials have been used in civil engineering applications by numerous researchers (Nishigaki 2000, Poon and Chan 2006, Cameron et al. 2013, Tatsuoka et al. 2013, Rahman et al. 2014, Garach et al. 2015, Murugan et al. 2016, Jindal and Ransinchung 2018, Martinho et al. 2018). Rahman et al. (2014) reported crushed brick (CB), RCA and reclaimed asphalt pavement (RAP) to be suitable backfilling materials for stormwater and sewer pipes. RCA and CB have been used for unbound sub-base materials (Poon and Chan 2006, Cameron et al. 2013, Garach et al. 2015). Blast furnace slag has been found suitable for use in road sub-bases (Nishigaki 2000). Tatsuoka et al. (2013) reported that well-compacted crushed concrete aggregate (CCA) can be used as backfill material for civil engineering soil structures requiring high stability. Waste Glass (WG) has been used in pavements for several decades. Jamshidi et al. (2016) presented a thorough review of the use of WG on the structural performance, durability and sustainability of asphalt, concrete and concrete block pavements. Murugan et al. (2016) used waste tyre crumb rubber to partially replace river sand in concrete block pavers in an attempt at improving the durability and sustainability of the blocks. Jindal and Ransinchung (2018) used RCA, industrial waste (fly ash) and agricultural wastes (rice husk ash and bagasse ash) in concrete pavements. Admixing industrial or agricultural wastes with pozzolanic properties enhances the strength and improves the durability of concrete thus making them as good as conventional concrete (Jindal and Ransinchung 2018). Martinho et al. (2018) used RCA as substitutes of natural aggregates to produce asphalt mixtures.

Numerous researchers (Nishigaki 2000, Rizvi et al. 2010, Bhutta et al. 2013, Çetin 2015, Jang et al. 2015, Khankhaje et al. 2017, Monrose et al. 2019, Yao et al. 2019, Tavares and Kazmierczak 2016, David et al. 2018) have reported on the incorporation of recycled waste materials or recycled industrial by-products in permeable pavement surfaces, porous concrete in particular. Nishigaki (2000) used blast furnace slag in permeable paving blocks. Khankhaje et al. (2017) compared the effect of using two different sizes of oil palm kernel shell and cockle shell as partial replacement of natural coarse aggregate on the properties of pervious concrete pavement. Khankhaje et al. (2017) reported a decrease in compressive strength of the pervious concrete with increased shell contents but suggested that the values obtained satisfied the requirements for lightly traffic areas such as parking lots and footpaths. Rizvi et al. (2010) evaluated the use of RCA from old curb and gutter, sidewalks and sewers in pervious concrete pavement and found that up to 15% of natural course aggregate could be replaced with RCA without affecting the structural and hydraulic performance of the pervious concrete. Çetin (2015) incorporated recycled household plastics (low density polyethylene [LDPE]) as a supplemental aggregate (1, 3, and 6%) in porous asphalt to produce a permeable plastic pavement. Tavares and Kazmierczak (2016) used RCA from construction and demolition waste in pervious concrete and found that mean 28–day compressive strengths were within the expected range (2.8 – 28 MPa or 400 – 4000 PSI) for pervious concrete. David et al. (2018) found similar performance characteristics when comparisons of compressive strength, density and surface infiltration rate of pervious concrete containing RAP and waste tire rubber were made with pervious concrete that was made up of natural aggregate without additions. Monrose et al. (2019) used manufactured lightweight aggregates referred to as Carbon-Negative Aggregates in solid paving blocks and reported that CNA could replace natural course aggregates in these blocks by up to 100%.

Meanwhile, only a handful of studies (Sañudo-Fontaneda et al. 2014, Rahman et al. 2015b, Rodriguez-Hernandez et al. 2015) have reported on the utilisation of recycled waste materials as reservoir aggregates in permeable pavements. Rahman et al. (2015a), during a laboratory study, found RCA and CB to be suitable alternative sub-base material for permeable pavements. In the same study, Rahman et al. (2015b) investigated the hydraulic performance and pollutants removal efficiency of PPS using CB, RCA and RAP in combination with geotextile and reported that the geotechnical and hydraulic properties of these recycled waste materials in the pavement filter layers were consistent or superior to that of typical quarry aggregates. Rodriguez-Hernandez et al. (2015) reported that Recycled Aggregates (RA) from Construction and Demolition Waste (CDW) as sub-base materials in permeable pavements improved the hydrological output of the permeable pavements in terms of attenuation, retained rainfall, peak outflow and time to peak. Sañudo-Fontaneda et al. (2014) used basic oxygen furnace slag as sub-base materials in permeable pavements and reported water quality improvements in terms of Total Suspended Solids, turbidity and Dissolved Oxygen.

Recycled waste materials obtain their physical and chemical properties from their sources, processing methods, and handling techniques which in turn determine their suitability for use in construction with respect to structural (strength and durability) and environmental (leachability) requirements (Inyang 2003). According to Arulrajah et al. (2013) different researchers have found that construction rubble possesses few negative environmental and social effects because leachate release and the presence of heavy metals are within acceptable limits for civil engineering applications.

From the lack of literature sources, it is evident that a research gap exists that involve the assessment of the performance of PPS wherein recycled waste materials are incorporated as filter materials in pavement storage reservoirs. This paper seeks, therefore, to assess the suitability of two recycled waste materials; Crushed Concrete Aggregate (CCA) and a novel material referred to as Cement-bounded Expanded Polystyrene (C-EPS) as filter materials for use in sub-base reservoirs of permeable pavements. The evaluation has two objectives. Firstly, the physical characteristics of CCA are compared to that of natural quarried materials of basalt and quartzite aggregates. Secondly, the pollutant removal efficiencies of four 0.2 m^2 permeable pavement rigs containing either natural or recycled sub-base materials are determined and compared. The pollutant removal assessment involved the retrieval of "grab" samples of stormwater runoff from various urban settings across Trinidad. The samples were judiciously applied over the various pavements using a custom-built rainfall simulator. Outflow lasted between 7 and 10 minutes during each test run after which effluent samples were collected for water quality testing and analysis.

Expanded polystyrene (EPS) is a very low-density foam which contains discrete air voids in a polymer matrix (Cook 1983). The EPS particles are manufactured by thermal expansion of polystyrene particles saturated with n-pentane. EPS particles are microbiologically stable, float in water, swell in petroleum and demonstrate resistance to mineral acids (with the exception of nitric acid) and bases. They are soluble in organic solvents such as ketones and aromatic hydrocarbons and are thermally stable between 0°C (32°F) and 90°C (194°F). Toxicity of polystyrene depends on the content of the monomer, which can be easily removed by washing with water (Sokolović et al. 2009). EPS is usually deemed an environmental menace because it is not bio-degradable. However, it can easily be recycled into a product which can be utilised in practical sustainable construction (Mwasha et al. 2013). EPS is 100% recyclable and thousands of tonnes are recycled each year in developed countries such as the UK (Ngugi et al. 2017). The common characteristics, handling and uses of EPS has been discussed in detail by Mwasha et al. (2013).

The literature surrounding the use of EPS in civil engineering applications is mostly devoted to lightweight EPS concrete wherein the mechanical properties of these materials are assessed. Quarried aggregate is typically replaced with varying percentages of EPS beads depending upon structural requirements (density and strength) (Kan and Demirboğa 2009, Babu et al. 2005, Kaya and Kar 2016, Bouvard et al. 2007, Xu et al. 2012, Chen and Liu 2004). EPS blocks have been used worldwide as a type of geofoam lightweight fill material, typically used in embankments where the long-term applied stresses do not exceed circa 100 kPa (2000 lbs/ft^2) (Ngugi et al. 2017). EPS has further been used a recycled material in asphalt. Baker et al. (2016) blended asphalt (bitumen) with recycled packaging waste polystyrene instead of common polymer. They suggested that the modified polystyrene-asphalt binder, had the potential of performing satisfactorily under hot climatic conditions and could be used for lightly-loaded areas such as playgrounds, training areas, parking lots and sidewalks.

Few studies (Sokolović et al. 2009, Schöntag et al. 2015, Orlov et al. 2016, Osuagwu et al. 2018) have reported on the use of EPS as a filter material for water/wastewater treatment and no studies, to the authors' best knowledge, have reported on the use of EPS in permeable pavements. Sokolović et al. (2009) investigated, using a laboratory pilot filter, the efficiency of separation of iron hydroxide flocks from water through an EPS filtration bed. Schöntag et al. (2015) compared the pollutant removal efficiencies of rapid filters made either of sand and anthracite coal or polystyrene (PS) granules. The authors reported that the two filter types achieved similar performances. Additionally, the PS granules did not release detectable amounts of styrene in the water and can therefore be used as filter media. The authors did note, however, that monitoring for long term degradation and the possibility of leaching of styrene into the water was recommended. Orlov et al. (2016) argued that the cost of potable water treatment schemes is largely dependent on the cost of the filtration system and suggested that in Ukraine, filters made up of EPS as opposed to sand could provide savings in capital investment by 40–50%, in operating costs by 30–40% and in electricity by 7–9%. Osuagwu et al. (2018) used EPS as a viable adsorbent for the removal of iron was raw water. They reported 36% iron removal efficiencies within a contact time of 5 mins.

Materials and Methods

Design and construction of permeable pavement rigs

Permeable pavement rigs were designed in accordance with technical guidance from literature sources (Collins et al. 2008, Scholz and Grabowiecki 2007, Drake et al. 2013, Bentarzi et al. 2016). Moreover, numerous institutions worldwide have provided general guidance relating to the design and construction of permeable pavements. In the UK, British Standard BS 7533-13 (BSI 2009a) offers guidance on the design of permeable pavements. Likewise, the Interlocking Concrete Pavement Institute ICPI (2016) has also provided industry guidance for PICP in the U.S.A. and Canada. Similarly, in Australia, the Concrete Masonry Association of Australia (CMAA) has freely made available several design guidance manuals on permeable paving on their website (CMAA 2016). Each of these standards provides 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 scarce across Caribbean SIDS. Consequently, only certain recommendations from these industry guidelines along with previous studies relating to aggregate gradations and pavement layer thicknesses were considered in this research.

Four 450 × 420 × 610 mm (18 × 16.5 × 24 in.) permeable pavement rigs were constructed from 19 mm (3/4 in.) construction plywood as a tanked system. The rigs were made watertight by inserting a 2 mm thick layer of commercially available PVC based pond liner on the inside. Three 12.5 mm (1/2 in.) PVC outflow pipes were inserted through one face of each rig at varying heads of 50, 250 and 480 mm (2, 10 and 19 in.), above the base of the rigs. Three of the four rigs are shown in Figure 1.

The rigs were made up of an 80 mm (3.1 in.) deep I-Paver interlocking concrete block surface, a 50 mm (2.0 in.) deep bedding layer, a geotextile layer, a 100 mm (4.0 in.) deep base course and a 250 mm (10.0 in.) deep sub-base layer. The I-Pavers were supplied by a concrete block manufacturer in Trinidad. Each block paver unit measured 80 × 197 × 143 mm (3.1 × 7.8 × 5.6 in.) and weighed 4.35 kg (9.6 lbs).

The bedding layer consisted 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 aggregate. The sub-base layer comprised of either 19 mm (3/4 in. sieve) ASTM No.5 aggregates or C-EPS. The varying sub-base materials used during the course of the study are listed in Table 1. CCA was obtained by crushing and sieving aged precast concrete cylinders in the laboratory. A 450 × 420 × 250 mm C-EPS rigid filter block (Figure 2) was prepared in the laboratory. The materials used were Premium Plus

Cement (PPC) which contains approximately 30% pozzolanic material and 70% Ordinary Portland Cement (OPC), tap water and EPS beads. The PPC was sourced from a local manufacturing plant (Trinidad Cement Limited, Claxton Bay, Trinidad, W.I). PPC is manufactured in accordance with international standards (EN 197-1 2011, ASTM International 2017). According to the manufacturer, PPC is an eco-friendly cement option whose production has significantly reduced the manufacturer's carbon footprint. The EPS beads were also sourced from a local supplier (Mecalfab Limited, O'meara Industrial Estate Arima, Trinidad, W.I.). Prior to the production of the final C-EPS block, repetitious and numerous trial mixes were done which lead to an optimum mix design. Mixes were evaluated based on hydraulic conductivity and compressive strength characteristics. The optimum mix is presented in Table 2. The mixes ensured that excessive amounts of cement were not utilised. This was necessary to produce a filter material with adequate hydraulic conductivity.

For each mix, three 50 × 70 mm cylindrical samples were prepared in PVC sample holders. These samples were used for hydraulic conductivity (coefficient of permeability) testing using the falling head method (Das 2010). Plumbers putty was used to seal around the top edge of the cylinder to prevent water from bypassing the sample. The C-EPS sample preparation for the falling head test is shown in Figure 3. For compressive strength testing, two 100 × 200 mm and six (6) 150 × 300 mm cylinder samples and six (6) 100 mm cube samples were prepared in accordance with BS EN 12390-3:2009 (BSI 2009b) and ASTM C936 (ASTM International 2018a) respectively. All samples were secured, de-moulded after 24 hours, labelled and cured in water at a standard temperature of 20 ± 1 °C for at least 28 days prior to testing. Low compressive strengths were expected, hence a Tinius Olsen tension and compression testing machine (Tinius Olsen TMC, Pennsylvania USA) was used as opposed to a traditional concrete compressive strength testing apparatus. Prepared samples and compressive strength testing are shown in Figure 4. All compressive strength results were less than 1.0 MPa.

The chemical compositions of the CCA and C-EPS were determined using an X-ray fluorescence spectrometer (XRF) model SRS 3400 (BRUKER AXS, Inc., Madison, Wisconsin, USA). An ELTRA CS2000 Carbon/Sulphur Determinator (ELTRA GmbH, Haan, Germany) was used to determine the percentage of Carbon and Sulphur present. Compound identification was carried out using a Bruker-Axs X-Ray Diffractometer (XRD) Model D8 Advance (BRUKER AXS, Inc., Madison, Wisconsin, USA). For each material, approximately 500g of fines passing the No. 12 (1.7 mm) sieve was used for analysis. Results from the XRF are presented in Table 3. CCA contained mostly CaO and SiO_2 at 29% and 62% respectively whereas C-EPS consisted predominantly of CaO, SiO_2 and C at 52%, 16% and 20% respectively.

For all rigs, a nonwoven geotextile layer was placed between the bedding layer and the aggregate base course layer. The properties of the geotextile layer are listed in Table 4. The Minimum Average Roll Value (MARV), as defined in ASTM D4433 (ASTM International 2018b), is a manufacturing quality control tool used to provide purchasers/users a 97.7% degree of confidence that any samples will exceed reported values. Numerous researchers have reported on the ability of geotextiles to improve short-term pollutant removal efficiency (Rahman et al. 2015b, Tota-Maharaj et al. 2012) as well as improving infiltration and attenuation (Nnadi et al. 2014) of permeable pavements.

Geotechnical and physical testing

The geotechnical and physical tests conducted on the pavement aggregates are listed in Table 5. In addition to these tests, particle size distribution tests of the aggregates were performed by sieve analysis in accordance with ASTM C136 (ASTM International 2014b).

Water quality testing

Sampling and Testing Methods

Rather than using synthetic stormwater as per numerous studies (Tota-Maharaj and Scholz 2010, Myers et al. 2011, Rahman et al. 2015b, Sounthararajah et al. 2017, Jayakaran et al. 2019), this research project utilised stormwater runoff samples extracted during rainfall events at various locations across Trinidad. To this end, a manual "grab" method of collecting samples of stormwater runoff was used. Grab samples are discrete samples of fixed volume taken to represent local conditions in the flow (Butler and Davies 2011). Attempts were often made to capture representative "first flush" samples. These "first flush" samples typically contain the largest percentage of the total contaminant loadings especially in small catchment areas with predominantly impervious surfaces and which experience high intensity storms (Geosyntec Consultants and Wright Water Engineers 2009). These high intensity rainfall events are commonplace in Trinidad. First flush samples were not always obtained due to difficulties in estimating the timing of rainfall events. This made weather forecasting a crucial aspect of the sampling efforts.

A total of thirty (30) individual 100 L grab samples were collected from rainfall events between December 2016 and August 2018. Five (5) 20 L polyethylene buckets were used in this regard. Trinidad has an annual rainfall depth of approximately 2000 mm. There is a strong seasonal variation in rainfall whereby 75 to 80% of rainfall is received during the wet season (June to December). The remaining 20 to 25 % is received during the dry season (January to May) (Monrose and Tota-Maharaj 2018).

Captured stormwater runoff samples were applied uniformly over the rigs using a purpose-built rainfall simulator at intensities not exceeding 2.0 L/min. Numerous studies (Alsubih et al. 2016, Nnadi et al. 2015, Sounthararajah et al. 2017) have successfully used rainfall simulation techniques in their research. Outflow (effluent) exited at the outlet of the permeable pavement rigs and was permitted to flow for several min (7 to 10 min) prior to collection in 300 ml sampling bottles for analysis. Throughout the stormwater application events, the influent (raw stormwater) was continuously stirred to ensure particles remained in suspension. The collected outflow samples were analysed immediately or refrigerated at 4 ºC to minimise any changes in the physio-chemical properties of the samples prior to analyses. A schematic of the experimental set up is shown in Figure 5. It is made up of a 100 L storage mixing container equipped with a submersible pump and a variable-speed heavy-duty mixer, valves to control flow rates, flow meters to measure flow rates and perforated PVC pipes to distribute the stormwater. Outflow exited the permeable pavement rigs through a 12.5 mm outflow pipe located at the base of each rig.

Water quality analyses

The pollutant removal efficiencies of the four (4) rigs were compared through analysis of various influent and effluent water quality parameters – pH, Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Electroconductivity (EC), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Nitrate-Nitrogen (NO_3-N), reactive phosphorous (PO_4^{3-}), sulphates (SO_4^{2-}) and turbidity (Nephelometric Turbidity Unit [NTU]). All water quality sample analyses were in accordance with the American Public Health Association standard methods for the examination of water and wastewater (APHA 1998).

Table 6 identifies the standard methods used in this paper and the Minimum Detectable Levels (MDL) for each parameter. pH was measured using an Orion 3 Star benchtop meter

(Thermo Scientific, Beverly, MA, USA). DO was measured using a YSI 5000 Benchtop DO Meter and probe (YSI, Yellow Springs, OH, USA). A Jenway 4520 Conductivity meter (Jenway, Staffordshire, UK) was used to measure electroconductivity (µS/cm). A Hach Colorimeter (DR/820) (Hach, Loveland, CO, USA) was used to measure NO_3-N (mg/L), SO_4^{2-} (mg/L), PO_4^{3-} (mg/L), and turbidity (Nephelometric Turbidity Units [NTU]). The concentration of NO_3-N (mg/L) was determined by a cadmium reduction method using Hach NitraVer5 Nitrate reagent powder pillows. SO_4^{2-} (mg/L) was measured by the SulfaVer 4 Method using Hach SulfaVer 4 sulphate reagent powder pillows. PO_4^{3-} (mg/L) was measured by the Amino Acid method using Hach Molybdate and Amino acid reagents. The Absorptometric method was used to measure turbidity. COD was analysed using a Hach DRB200 Reactor block (Hach, Loveland, Colorado, USA) (for sample digestion) and a Hach Spectrometer (DR/5000) TNT 822 COD vial (Hach, Loveland, CO, USA). COD was measured rather than BOD due to ease of measurement and the correlation between the two parameters. A similar approach was taken by Pilon et al. (2019) for evaluating the effect of porous concrete on water quality parameters in Alcoa, TN, USA. TDS (mg/L) and TSS (mg/L) were measured using a 0.45 µm Whatman filter paper.

Data analysis

Statistical analyses of the results were performed using the IBM statistical software Statistical Package for the Social Sciences (SPSS) version 20 (IBM 2011). Descriptive statistics, tests for normality using goodness-of-fit statistics, one-way analysis of variation (ANOVA), Pearson's correlations and the Mann-Whitney U two-independent samples tests were used for the analysis all water quality parameters. A 95% confidence interval was used for all statistical analyses. Boxplots and bar charts were used to examine and present variations and/or similarities in mean pollution concentration results. Mean pollutant removal efficiencies were calculated from

Equation (1).

$$\text{Removal efficiency (\%)} = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) \times 100 \quad (1)$$

where C_{in} is the inflow (influent) concentration and C_{out} is the outflow (effluent) concentration for individual samples.

Results and Discussion

Physical and geotechnical characteristics

The physical and geotechnical characteristics of the various construction aggregates used in the rigs are present in Table 7. The specific gravity of the CCA was as expected, lower than that of basalt and quartzite aggregates but greater than the typical requirement of 2.0 kg/m^3 (Rahman et al. 2015b). Conversely, water absorption of the CCA was significantly higher than that of basalt and quartzite aggregates but less than the typical requirement of 10% (Rahman et al. 2015b). Nevertheless, it fell at the low end of the 6 to 14% range of acceptable water absorption values for recycled materials in civil engineering applications (Poon and Chan 2006). The CCA performed remarkably well under the LA abrasion and impact tests with results better than the quartzite aggregates and below 50%. It must be noted that a significant portion of the abrasion was due to the disintegration of the cementitious paste (mortar) which surrounded the natural aggregates. The pH of the CCA was notable, being significantly higher than the basalt and quartzite aggregates. This high pH value indicates high alkalinity which can be attributed to the chemical composition of the cementitious paste which is rich in calcium hydroxide $Ca(OH)_2$ and other compounds (Table 3). This is consistent with results provided by Rahman et al. (2015a) who reported slightly less alkaline values for RCA (10.5) and CB (9.5) and stated that these values were within expected limits. Based on these physical measurements, CCA demonstrated the potential to be a suitable construction material to substitute or add to traditional quarried materials in permeable pavement applications. The particle size distribution (PSD) or gradation curves of the aggregates used in each test rig are shown in Figure 6. The bedding course, base course and sub-base course aggregates fall into ASTM grading classifications No.8, No.57 and No.5 respectively.

With regards to the C-EPS, average hydraulic conductivity values ranged from 1330 to 1764 mm/h which were satisfactory for this application. Compressive strength results were, however, relatively low; below 1.0 MPa. Hence, from a structural view point, C-EPS is recommended for use in permeable pavements non-traffic areas such as building aprons, sidewalks, footpaths, landscapes, pedestrian access and bicycle lanes.

Water quality testing

Influent runoff characteristics

Table 8 presents descriptive statistics (range, mean [$\bar{x}$], standard deviation [σ] and standard error of the mean [$\sigma_{\bar{x}}$]) of the influent samples along with the Maximum Permissible Level (MPL) of water pollutants discharged into the environment according to the Trinidad and Tobago Environmental Management Authority (EMA), and the United States Environmental Protection Agency (US EPA).

Test for normality

The results of the test for normality using the one-sample Kolmogorov-Smirnov and Shapiro-Wilk goodness-of-fit measures in SPSS are presented in Table 9. Water quality parameters where the null hypothesis is true follow a normal distribution if $p > 0.05$ and are formatted as ***bold italics***.

The distribution required transformation where $p < 0.05$. Since the bulk of the data violated conditions for data normality, which limited the use of standard parametric testing, non-parametric statistical tests were utilised.

Analysis of variance

The one-way analysis of variance (ANOVA) in SPSS was used to determine whether there were any statistically significant differences between the means of the water quality parameters from at least two of the rigs. The results are presented in Table 10. The null hypothesis suggests that the means of each water quality parameter is the same across all rigs. The null hypothesis was rejected ($p < 0.05$) for all parameters except COD, NO_3-N, turbidity and TSS.

Correlation analysis

The bivariate correlation function in SPSS was used to evaluate the strengths of the relationships between the varying pavement rigs (sub-base variations) and the outflow pollutant concentrations. The nonparametric Pearson's correlation coefficient was used to determine the strength of the correlations, if present, whilst the *p*-values determined the significance of the relationships. The results of the bivariate correlation analysis using Pearson's coefficients are presented in Table 11. A 95% confidence level was used. The results showed that all pavement rigs were significantly correlated ($p < 0.01$) with the water quality parameters in all cases except COD, NO_3-N, turbidity and TSS ($p > 0.05$). These results support the ANOVA results presented in Table 10.

To further analyse the significance of the distribution of water quality parameter results between each pair of rigs, Mann-Whitney two-independent samples tests at a confidence level of 95% were used. The results of these analyses are listed in Table 12. It is noticeable that for all parameter distributions, there were no significant differences ($p < 0.05$) between the distributions for Rigs 1 and 2, both of which contained natural aggregates in their sub-base layer. The distributions are therefore statistically equal between Rigs 1 and 2 for all parameters. There was significant evidence ($p < 0.05$) to show that the distribution of 60% of the water quality parameters are different between rig groups 1 vs. 3; 1 vs. 4; 2 vs. 3 and 2 vs. 4. In other words, the distribution of all water quality parameters except COD, NO_3-N, turbidity and TSS were significantly different ($p < 0.05$) between a rig which contained natural aggregates in the sub-base to a rig containing recycled material. This was not surprising given the composition of the recycled materials used (Table 3). Comparisons between Rigs 3 and 4 which contained CCA and C-EPS respectively, showed that the distribution of 50% of the water quality parameters were significantly different ($p < 0.05$).

Change in pH

pH determines the acidity or alkalinity of a water/wastewater sample by measuring the fraction of hydrogen (H^+) and hydroxyl (OH^-) ions present in the sample (Tota-Maharaj 2010). Figure 7 shows box and whiskers plots for influent and effluent pH values for the rigs. Influent values ranged from 6.7 to 10.4 with a mean of 8.1 ± 1.1 (Table 8). Notable differences in mean effluent values were observed between the rigs with natural materials to those with recycled materials. The ANOVA (Table 10) showed significant variations of pH ($p < 0.01$) across the rigs. This confirms the pattern of pH distribution observed in Figure 7. Mean effluent pH values from Rig 1 (7.8 ± 0.1) and Rig 2 (7.9 ± 0.1) were neutral as compared to the alkaline mean effluent pH values from Rig 3 (12.0 ± 0.1) and Rig 4 (12.3 ± 0.1). The high pH values from Rigs 3 and 4 can be attributed to the dissolving of calcium hydroxide, $Ca(OH)_2$ from the hardened cement paste as the stormwater percolated through the sub-base materials. The $Ca(OH)_2$ was produced from cement hydration and the soluble metal alkalis present in cement (Dhir and Jackson 1996). A similar explanation was provided by Zhang et al. (2018) for the reported high pH values obtained from permeable pavements with porous concrete and cement brick surfaces. However, the effluent pH from porous concrete surfaces tend to decrease over time due to the carbonation of the porous concrete. Guidelines for reuse of stormwater for domestic use or irrigation set a pH range of 6 to 9 (US EPA 2012). Outflow from Rigs 3 and 4 would therefore most likely not be suitable for these types of reuse without further treatment. However, permeable pavements with high pH effluents can be beneficial and behave like a buffer for acidic rainfall events (Collins et al. 2010, Kazemi and Hill 2015, Razzaghmanesh and Borst 2019). Effluent pH from permeable pavements is highly reflective of the composition of the materials used within the pavement structure. Numerous studies have reported increases in pH effluents from permeable pavements consisting of porous concrete (Collins et al. 2010, Drake et al. 2014b, Crookes et al. 2017, Vadas et al. 2017, Zhang et al. 2018, Pilon et al. 2019), porous asphalt (Jayakaran et al. 2019, Razzaghmanesh and Borst 2019), slag sub-base aggregates (Sañudo-Fontaneda et al. 2014) and calcite sub-base aggregates (Reddy et al. 2014).

Change in Chemical Oxygen Demand (COD)

COD measures the organic strength of wastewaters in terms of the total quantity of oxygen required for oxidation to CO_2 and H_2O (Sawyer et al. 2003). The COD is widely used as a measure of the susceptibility to oxidation of the organic and inorganic materials present in water bodies (Chapman and Kimstach 2002). Box and whiskers plots for influent and effluent COD concentrations along with average removal efficiencies are presented in Figure 8. Influent COD concentrations ranged from 35.1 to 119.0 mg/L with a mean of 70.9 ± 21.8 mg/L. The ANOVA (Table 10), Pearson's correlation tests (Table 11) and the Mann-Whitney U two-independent samples tests (Table 12) showed no statistically significant difference ($p > 0.05$) between rigs with respect to COD effluent concentrations. COD removal was similar amongst all rigs, ranging from 4.2% (Rig 2) to 7.2% (Rig 1). Rigs 3 and 4 reduced COD by 4.5% and 6.5% respectively. The decrease in COD can most likely be attributed to the aerobic conditions and the subsequent oxidation of pollutants and organic material within permeable pavement rigs (Pilon et al. 2019). Zhang et al. (2018) found that after 48 h residence time, a permeable pavement containing shale bricks at the surface removed COD by approximately 46%. Balades et al. (1995) reported that COD was reduced by a porous pavement by 80 to 90%. Pilon et al. (2019) reported 36% reduction in COD from a porous concrete section of a parking lot in Alcoa, TN, USA.

Change in Dissolved Oxygen (DO)

Dissolved Oxygen (DO) determination measures the amount of dissolved (or free) oxygen present in a water or wastewater sample (Hammer and Hammer Jr. 2007). In liquid wastes, DO determines whether the biological changes result from aerobic or anaerobic organisms (Sawyer et al. 2003). Oxygen is essential to all forms of aquatic life, including those organisms responsible for the self-purification processes in natural waters. In freshwaters, DO at sea level ranges from 15 mg/L at 0 °C to 8 mg/L at 25 °C. Concentrations less than 5 mg/L may threaten the functioning and survival of biological communities and below 2 mg/L may lead to the death of most fish (Chapman and Kimstach 2002). Mean DO influent and effluent concentrations and removal efficiencies are presented in Figure 9. Influent DO values had a mean of 7.19 ± 0.75 mg/L ranging from 5.67 to 8.46 mg/L. The ANOVA (Table 10) showed significant differences in DO ($p < 0.01$) across the rigs. DO was slightly reduced by 2% in Rigs 1 and 2. Rigs 3 and 4 on the contrary, produced a slight increase in DO by 3% and 5% respectively. This result was not expected and required further research.

Further DO analysis was conducted on Rig 4 which sought to determine the most likely cause of increased DO concentrations. A modified approach was taken whereby six different influent samples of varying DO concentrations were poured into and stored in Rig 4 for a residence time ranging from 4 to 26 days for each sample. Results of the effluent DO measurements made are presented in Figure 10. All DO concentrations increased (except for the case of distilled water) from their initial values to an average constant value of circa 7.5 mg/L. DO values increased by 200% in some samples. It is common for the DO of stored water in permeable pavements to deplete as residence time increases (Kazemi and Hill 2015) because of microbiological activity. However, no odours signifying microbiological decay were detected during sampling events from Rig 4. Additionally, microbiological activity was not expected due to the high pH environment (Selvakumar and O'Connor 2018). The increased DO concentration results are once again inconclusive and require further research.

Change in Nitrate-Nitrogen (NO_3-N)

Nitrogen, which exists in four main forms (organic, ammonia, nitrite and nitrate) is of historical environmental concern in water which has led to the regulation of its concentration in surface waters for decades. Excessive levels of nitrogen, when discharged into receiving waters, can promote the growth of undesirable aquatic plants such as algae and floating macrophytes (Sawyer et al. 2003, Butler and Davies 2011). Box and whiskers plots for influent and effluent NO_3-N concentrations along with average removal efficiencies are presented in Figure 11. Influent NO_3-N concentrations ranged from 0 to 6.50 mg/L with a mean of 1.49 ± 1.52 mg/L. NO_3-N concentrations from Rig 4 were slightly higher than the other three rigs. The ANOVA (Table 10), Pearson's correlation tests (Table 11) and the Mann-Whitney two-independent samples tests (Table 12) showed no statistically significant difference ($p > 0.05$) between rigs with respect to NO_3-N effluent concentrations. No rigs removed NO_3-N except for Rig 3. Rig 1 increased NO_3-N by 27%, Rig 2 by 21% and Rig 4 by 98%. Rig 3 reduced NO_3-N by 20%. Water infiltrating through permeable pavements tend to cause increases in NO_3-N (James and Shahin 1998) which could be attributed to aerobic conditions that were likely present throughout the pavement allowing ammonium-nitrogen (NH_4-N) to be nitrified to NO_3-N (Collins et al. 2010, Tota-Maharaj and Scholz 2010, Drake et al. 2014b, Razzaghmanesh and Borst 2019). Denitrification of nitrate (NO_3-) into nitrogen gas [$N_{2(g)}$] requires anoxic conditions which are unlikely to be present in a permeable pavement structure given that these pavements are designed to be free draining (Drake et al. 2014b). Numerous studies (James and Shahin 1998, Bean et al. 2007, Collins et al. 2010, Drake et al. 2014b, Braswell et al. 2018, Razzaghmanesh and Borst 2019), which have compared runoff from conventional asphalt pavements to effluent discharges from permeable pavements, have reported increased NO_3-N concentrations. However, a few studies (Pagotto et al. 2000, Gilbert and Clausen 2006) have shown a reduction in NO_3-N concentrations.

Change in Reactive Phosphorous (PO_4^{3-})

Phosphorous is an essential nutrient for living organisms and is present as both dissolved and particulate species in water. High levels of phosphorous in water may lead to eutrophication and algal growth (Chapman and Kimstach 2002). Box and whiskers plots for influent and effluent PO_4^{3-} concentrations along with average removal efficiencies are presented in Figure 12. Influent PO_4^{3-} concentrations ranged from 0.60 to 4.9 mg/L with a mean of 1.90 ± 1.09 mg/L. Mean effluent PO_4^{3-} concentrations ranged from 1.39 ± 0.82 (Rig 4) to 2.20 ± 0.0.79 (Rig 1). The ANOVA (Table 10) showed significant variations of PO_4^{3-} ($p < 0.01$) across the four rigs. Rigs 1 and 2 recorded slight increases in PO_4^{3-} of 22% and 9% respectively, while Rigs 3 and 4 had reductions of 18% and 33% respectively. The increases in PO_4^{3-} from rigs 1 and 2 can most likely be ascribed to the decomposition of organic matter present in the rigs. The removal of PO_4^{3-} from Rigs 3 and 4 can be attributed to the formation of phosphate salts from the reaction of PO_4^{3-} ions and the cementitious sub-base materials which lead to adsorption by the cementitious components. Wang et al. (2014) used cementitious materials for the sequestration of phosphorous from wastewater and reported removal rates of 80% for phosphorus concentrations ranging from 20 to 1000 mg/L. Agyei et al. (2002) removed PO_4^{3-} ions from aqueous solutions using fly ash, slag and Ordinary Portland Cement (OPC) and found that the rate and removal efficiency of PO_4^{3-} was linked to increasing CaO and/or Ca^{2+} ions in the adsorbents released into solution via hydration and dissolution. This agrees with the results presented in Figure 12 given that the CaO% (Table 3) was greater in C-EPS (Rig 4) than CCA (Rig 3). Deng and Wheatley (2018) reported that 2–5 mm recycled concrete aggregate (RCA) removed more than 90% of phosphorous from effluent and suggested that RCA could be used for both wastewater treatment and phosphorous recovery.

Change in Sulphate (SO_4^-)

Surface waters tend to contain SO_4^{2-}. Sources include atmospheric deposition of oceanic aerosols, leaching of sulphur compounds, industrial discharges or atmospheric precipitation. Bacteria can use sulphate as an oxygen source which is converted to hydrogen sulphide (H_2S, HS^-) under anaerobic conditions (Chapman and Kimstach 2002). Box and whiskers plots for influent and effluent SO_4^{2-} concentrations along with average removal efficiencies are presented in Figure 13. Influent SO_4^{2-} concentrations ranged from 0 to 77 mg/L with a mean of 17.8 ± 20.73 mg/L. The ANOVA (Table 10) showed significant variations of SO_4^{2-} ($p < 0.01$) across the four (4) rigs. Rigs 1 and 2 recorded significant increases in SO_4^{2-} (121% and 66% respectively) while Rig 3 and Rig

4 recorded 33% and 74% reductions in SO_4^{2-} respectively. Increases in SO_4^{2-} from Rigs 1 and 2 can most likely be attributed to the dissolution of SO_4^{2-} ions from the aggregates as water infiltrated through the rigs. Pilon et al. (2019) found a 157% increase in SO_4^{2-} from a pervious concrete pavement installed as a parking stall in Alcoa, TN, USA. They attributed this increase to the degradation of hydrocarbons or other organic compounds within the pavement structure or the creation of SO_4^{2-} by oxidation of another form of sulphur such as sulphide (S^{2-}). The high removal rates of SO_4^{2-} by Rigs 3 and 4 on the other hand, can most likely be attributed to the reaction of SO_4^{2-} ions and the cementitious sub-base materials leading to the formation of calcium sulphate ($CaSO_4$) and other salts which adhere to the sub-base materials. This reaction is essentially an attack by the SO_4^{2-} ions on calcium hydroxide [$Ca(OH)_2$], tricalcium aluminate (C_3A) and hydrated aluminate phases of the cement paste. The $Ca(OH)_2$ can convert to $CaSO_4$ as per Equation (2) and further to the subsequent growth of ettringite crystals as per Equation (3) (Miron and Magaña 2017).

$$\mathrm{Ca(OH)_2} + \mathrm{SO_4}^{-}{}_{\mathrm{aq.}} \rightarrow \mathrm{CaSO_4.2H_2}O \tag{2}$$

$$\mathrm{3CaSO_4.2H_2}O + C_3A + \mathrm{25H_2}O \rightarrow \mathrm{3CaSO_4.C_3A.31H_2}O \tag{3}$$

Change in Turbidity

The turbidity or cloudiness, of water may be defined as the interference of light passing through water by suspended matter such as silt, clay, organic matter, organic compounds, or dissolved inorganics (Sawyer et al. 2003, Alley 2007, Hammer and Hammer Jr. 2007). Suspended particles can be a significant health concern when heavy metals and hydrophobic chemicals such as pesticides adsorb to the particles (AWWA 2011). Box and whiskers plots for influent and effluent turbidity values along with average removal efficiencies are presented in Figure 14. Influent turbidity values ranged from 6 to 184 mg/L with a mean of 57.25 ± 54.21 mg/L. The ANOVA (Table 10), Pearson's correlation tests (Table 11) and the Mann-Whitney two-independent samples tests (Table 12) showed no statistically significant difference ($p > 0.05$) between rigs with respect to turbidity effluent values. All rigs had positive removal rates for turbidity with Rig 4 recording the highest (57%) while Rig 3 the lowest (10%). Rigs 1 and 2 reduced turbidity by 37% and 31% respectively. Some studies (Tota-Maharaj and Scholz 2010, Chowdhury et al. 2016) have reported turbidity removal rates in excess of 90% from permeable pavements while Pilon et al. (2019) reported no significant change in turbidity removal rates.

Change in Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) are the inorganic salts and dissolved materials in the filtrate from the TSS test (i.e. with a diameter < 0.45 µm) (Alley 2007, Butler and Davies 2011). Water with a high dissolved-solids content tends to have adverse impacts on irrigated crops, plants and grasses (Sawyer et al. 2003). Box and whiskers plots for influent and effluent TDS values along with average removal efficiencies are presented in Figure 15. Influent TDS values ranged from 22.00 to 400.00 mg/L with a mean of 196.82 ± 108.69 mg/L. Effluent TDS removal percentages were negative for all rigs. TDS increased by 48% from Rig 1, 31% from Rig 2, 212% from Rig 3 and 387% from Rig 4. These variations were confirmed by ANOVA (Table 10) which showed significant variations in mean TDS ($p < 0.01$) across the rigs. In general, TDS is directly related to EC (Chapman and Kimstach 2002) and as such the negative removal rates for TDS can be attributed to the dissolution of ions and other mineral fractions on the surface of the materials within the pavement structure (Myers et al. 2009) similarly to EC. As with high pH and EC, TDS values were high from Rigs 3 and 4 most likely because of the richness of CaO and other compounds present in the CCA and C-EPS (Table 3).

Change in Total Suspended Solids (TSS)

Total Suspended Solids (TSS) are the organic and inorganic solid matter maintained in suspension and retained upon evaporation and drying at 103 to 105 °C, when a sample is filtered through filter paper with a pore size of approximately 0.45 μm (Sawyer et al. 2003, Alley 2007, Butler and Davies 2011). The finer fractions of suspended solids (<63 μm) are extremely effective pollutant carriers. High concentrations of suspended solids pose harmful threats to receiving water, including increased turbidity and interference with numerous types of fish and aquatic invertebrates (Butler and Davies 2011). Box and whiskers plots for influent and effluent TSS values along with average removal efficiencies are presented in Figure 16. Influent TSS concentrations ranged from 18 to 386 mg/L with a mean of 131.95 ± 114.43 mg/L. Mean effluent TSS concentrations ranged from 46.50 ± 40.02 mg/L (Rig 4) to 64.48 ± 63.82 mg/L (Rig 1). The ANOVA (Table 10), Pearson's correlation tests (Table 11) and the Mann-Whitney two-independent samples tests (Table 12) showed no statistically significant difference ($p > 0.05$) between rigs with respect to TSS effluent concentrations. As expected, TSS removal percentages were relatively high for all rigs. TSS removal in permeable pavements is highly credited to sedimentation and mechanical filtration through the pavement structure. The entrapment (and thus removal) of most sediments is largely dependent on the size of the particulate matter and occurs within the top layers of the pavement structure (Brown et al. 2009, Lucke and Beecham 2011). Rig 1 had the lowest removal percentage of 52% whilst Rig 4 has the highest rate of 64%. Rigs 2 and 3 had removal percentages of 53% and 58% respectively. Based on the clarity of the samples collected, Rig 4 was seen to produce the highest TSS removal rates. Additionally, the increased filtration surface area of the C-EPS in the sub-base of Rig 4 provided for increased filtration of particulate matter. The presence of a geotextile layer between the bedding layer and the base course layer in all rigs also contributed to the removal of TSS. Numerous studies (Pratt 1997, Tota-Maharaj et al. 2012, Rahman et al. 2015b) have reported improved TSS removal efficiencies when geotextiles have been used in permeable pavements. Brown et al. (2009) assessed the processes and characteristics of solids removal in two types of permeable pavements in Canada and found that both pavement types removed 90% to 96% of suspended solids. Pilon et al. (2019) reported a 97% removal of TSS from a pervious concrete section of a parking lot in Alcoa, TN, USA.

Change in Electroconductivity (EC)

Electroconductivity (EC) or conductivity, measured in microsiemens per centimetre (μS/cm), is a measure of the concentration of dissolved ions/salts present in a given solution (Sawyer et al. 2003, Tota-Maharaj 2010). It is a measure of the ability of water to conduct an electric current and is sensitive to variations in dissolved solids, mostly mineral salts (Chapman and Kimstach 2002). Conductivity itself is not an aquatic or human health concern, but because it is easily measured, it can serve as an indicator of other water quality issues (Tota-Maharaj 2010). Mean EC concentrations and removal efficiencies for all rigs are presented in Figure 17. The results showed that EC values increased for all rigs. Rig 1 and Rig 2 had slight increases (33.5% and 17.2% respectively) whereas significant increases were observed from Rig 3 and Rig 4 (908% and 1895% respectively). These variations were confirmed by ANOVA (Table 10) which showed significant variations in mean EC values ($p < 0.01$) across the rigs. In general, the increases can be attributed to the dissolution of ions and other mineral fractions on the surface of the materials within the pavement structure (Myers et al. 2009). The composition of basalt and quartzite aggregates in the sub-base of Rigs 1 and 2 respectively, did not permit high levels of dissolution of ions. This was not the case for the CCA and C-EPS in Rigs 3 and 4 respectively. As with high pH, EC values were high from Rigs 3 and 4 most likely because of the richness of CaO and other metal compounds present in the CCA and C-EPS (Table 3).

Conclusion

This study evaluated the suitability of Crushed Concrete Aggregates (CCA) and a novel filter material referred to as Cement-bounded Expanded Polystyrene (C-EPS) as suitable sub-base materials in permeable pavements. The evaluation compared the physical characteristics of the recycled materials and pollutant removal efficiencies of permeable pavement rigs containing CCA and C-EPS to those made up of natural aggregates of basalt and quartzite aggregates. Natural stormwater runoff from various locations across Trinidad, West indies was used as the influent. This ensured that different levels of pollutant concentrations were assessed. Water quality parameters were analysed using the IBM statistical software SPSS version 20. Based on the results of this study, the following conclusions are made.

(1) Based on the physical measurements obtained, CCA demonstrated potential as a suitable construction material to substitute or compliment traditional quarried materials in permeable pavement applications.

(2) C-EPS have relatively low compressive strength, < 1.0 MPa. Hence, from a structural view point, C-EPS is recommended for use in permeable pavements in non-traffic areas such as building aprons, sidewalks, footpaths, landscapes, pedestrian access and bicycle lanes. To accommodate light vehicular traffic, structural modifications to the pavement structure such as an increase in the thickness of the base layer may be considered and evaluated.

(3) In terms of pollutant removal efficiency, Rigs 3 and 4 which contained CCA and C-EPS respectively, performed equally or better than their counterparts. On average, Rig 3

removed COD by 5%, NO_3^-N by 20%, PO_4^- by 18%, SO_4 by 33%, turbidity by 10% and TSS by 57%. On average, Rig 4 removed COD by 6%, PO_4^{3-} by 32%, SO_4^{2-} by 74%, turbidity by 57% and TSS by 64%. However, noticeable increases in pH, TDS and EC measurements were noted. These increases were driven by the cementitious nature of the recycled materials. Despite the reported increases, all mean effluent pollutant concentrations were within the Maximum Permissible Levels (MPLs) of water pollutants discharged into the environment according to the Environmental Management Authority (EMA), Trinidad and Tobago and the United States Environmental Protection Agency (US EPA). In this regard, the CCA and C-EPS performed satisfactorily as sub-base materials in the permeable pavement rigs.

(4) The results showed that, in general, CCA and C-EPS can be used as suitable filter materials in the sub-base reservoir of permeable pavements. However, from an environmental view point, further analysis through leaching tests on these materials is recommended.

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References

Abdollahian, S., *et al.* 2018. Stormwater quality benefits of permeable pavement systems with deep aggregate layers. *Environments,* 5(6), 68.

Agyei, N. M., Strydom, C. A. and Potgieter, J. H. 2002. The removal of phosphate ions from aqueous solution by fly ash, slag, ordinary Portland cement and related blends. *Cement and Concrete Research,* 32(12), 1889–1897.

Alley, E. R., 2007. *Water Quality Control Handbook.* 2nd Ed. ed. New York: McGraw-Hill.

Alsubih, M.*, et al.* 2016. Experimental study on the hydrological performance of a permeable pavement. *Urban Water Journal*, 1–8.

APHA, 1998. Standard Methods for the Examination of Water and Wastewater, 20th Edition. Washington, DC, USA: American Water Works Association (AWWA), American Public Health Association (APHA), Water Environment Federation (WEF).

Arulrajah, A.*, et al.* 2013. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering,* 25(8), 1077–1088.

ASTM International, 2014a. Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. West Conshohocken, PA USA: ASTM International.

ASTM International, 2014b. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. West Conshohocken, PA USA: ASTM International.

ASTM International, 2015. Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. West Conshohocken, PA USA: ASTM International.

ASTM International, 2016. Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate. West Conshohocken, PA USA: ASTM International.

ASTM International, 2017. Standard Specification for Portland Cement. West Conshohocken, PA USA: ASTM International.

ASTM International, 2018a. Standard Specification for Solid Concrete Interlocking Paving Units. West Conshohocken, PA USA: ASTM International.

ASTM International, 2018b. Standard Terminology for Geosynthetics. West Conshohocken, PA USA: ASTM International.

AWWA, 2011. *Water Quality & Treatment A handbook on Drinking Water.* 6th Ed. ed. New York: McGraw-Hill.

Babu, D. S., Babu, K. G. and Wee, T. H. 2005. Properties of lightweight expanded polystyrene aggregate concretes containing fly ash. *Cement and Concrete Research,* 35(6), 1218–1223.

Baker, M. B., *et al.* 2016. Production of sustainable asphalt mixes using recycled polystyrene. *International Journal of Applied Environmental Sciences,* 11(1), 183-192.

Balades, J. D., Legret, M. and Madiec, H. 1995. Permeable pavements: Pollution management tools. *Water Science and Technology,* 32(1), 49–56.

Bean, E. Z., Hunt, W. F. and Bidelspach, D. A. 2007. Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts. *Journal of Irrigation and Drainage Engineering,* 133(6), 583–592.

Beecham, S., Pezzaniti, D. and Kandasamy, J. 2012. Stormwater treatment using permeable pavements. *Proceedings of the Institution of Civil Engineers - Water Management,* 165(3), 161–170.

Bentarzi, Y., *et al.* 2016. Hydrodynamic behaviour of a new permeable pavement material under high rainfall conditions. *Urban Water Journal,* 13(7), 687–696.

Bhutta, M. A. R., *et al.* 2013. Properties of porous concrete from waste crushed concrete (recycled aggregate). *Construction and Building Materials,* 47, 1243-1248.

Borgwardt, S., 2006. Long-term in-situ infiltration performance of permeable concrete block pavement. *8th International Conference on Concrete Block Paving.* San Francisco, CA, USA, 1–12.

Bouvard, D., *et al.* 2007. Characterization and simulation of microstructure and properties of EPS lightweight concrete. *Cement and Concrete Research,* 37(12), 1666–1673.

Braswell, A. S., Winston, R. J. and Hunt, W. F. 2018. Hydrologic and water quality performance of permeable pavement with internal water storage over a clay soil in Durham, North Carolina. *Journal of Environmental Management,* 224, 277–287.

Brattebo, B. O. and Booth, D. B. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research,* 37(18), 4369–4376.

Brown, C., *et al.* 2009. Characteristics of sediment removal in two types of permeable pavement. *Water Quality Research Journal of Canada,* 44(1), 59–70.

BSI, 1990. Testing aggregates. Method for determination of aggregate impact value (AIV). London, UK: British Standard Institution BSI.

BSI, 2009a. Pavements constructed with clay, natural stone or concrete pavers. Guide for the design of permeable pavements constructed with concrete paving blocks and flags, natural stone slabs and setts and clay pavers. London, UK: British Standard Institution BSI.

BSI, 2009b. Testing hardened concrete. Compressive strength of test specimens. London, UK: British Standard Institution BSI.

BSI, 2012. Tests for geometrical properties of aggregates. Determination of particle shape. Flakiness index. London, UK: British Standard Institution BSI.

BSI, 2018. Methods of test for soils for civil engineering purposes. Chemical and electro-chemical tests. London, UK: British Standard Institution BSI.

Butler, D. and Davies, J. W., 2011. *Urban Drainage.* 3rd edn. ed. New York, USA: Spon Press.

Cameron, D*., et al.*, 2013. The use of recycled aggregates in unbound road pavements. *18th International Conference on Soil Mechanics and Geotechnical Engineering.* Paris, France: Presses des Ponts, 3187–3190.

Çetin, M. 2015. Consideration of permeable pavement in landscape architecture. *Journal of environmental protection and ecology,* 16(1), 385–392.

Chang, N*., et al.* 1999. The assessment of reuse potential for municipal solid waste and refuse-derived fuel incineration ashes. *Resources, Conservation and Recycling,* 25(3–4), 255–270.

Chapman, D. and Kimstach, V., 2002. Selection of Water Quality Variables. *In:* Chapman, D. ed. *Water Quality Assessments: A guide to the use of Biota, Sediments and Water in Environmental Monitoring.* 2nd ed. Boca Raton, Fl, USA: CRC Press.

Charlesworth, S. M., Beddow, J. and Nnadi, E. O. 2017. The Fate of Pollutants in Porous Asphalt Pavements, Laboratory Experiments to Investigate Their Potential to Impact Environmental Health. *International Journal of Environmental Research and Public Health,* 14(6), 666.

Cheeseman, C. R., Makinde, A. and Bethanis, S. 2005. Properties of lightweight aggregate produced by rapid sintering of incinerator bottom ash. *Resources, Conservation and Recycling,* 43(2), 147–162.

Chen, B. and Liu, J. 2004. Properties of lightweight expanded polystyrene concrete reinforced with steel fiber. *Cement and Concrete Research,* 34(7), 1259–1263.

Chowdhury, R. K., Sharvelle, S. E. and Beecham, S. 2016. Greywater quality changes in a permeable pavement reservoir. *Proceedings of the Institution of Civil Engineers - Water Management,* 169(4), 190–198.

CMAA, 2016. *Permeable Paving* [online]. Available from: http://www.cmaa.com.au/technical [Accessed 11 November 2016].

Collins, K. A., 2007. *A field evaluation of four types of permeable pavement with respect to water quality improvement and flood control.* Thesis (MSc.). North Carolina State University.

Collins, K. A. and Hunt, W. F., 2008. Permeable pavement: Research update and design implications. *Urban waterways.* Raleigh, NC: North Carolina State University, North Carolina Cooperative Extension Service.

Collins, K. A., Hunt, W. F. and Hathaway, J. M. 2008. Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina. *Journal of Hydrologic Engineering,* 13(12), 1146–1157.

Collins, K. A., Hunt, W. F. and Hathaway, J. M. 2010. Side-by-side comparison of nitrogen species removal for four types of permeable pavement and standard asphalt in eastern North Carolina. *Journal of Hydrologic Engineering,* 15(6), 512–521.

Cook, D. J., 1983. Expanded polystyrene concrete. *In:* Swamy, R. N. ed. *Concrete Technology & Design Vol. 1: New Concrete Materials.* London: Surrey University Press, 41-69.

Crookes, A. J., Drake, J. A. P. and Green, M. 2017. Hydrologic and Quality Control Performance of Zero-Exfiltration Pervious Concrete Pavement in Ontario. *Journal of Sustainable Water in the Built Environment,* 3(3), 06017001.

Das, B. M., 2010. *Fundamentals of Geotechnical Engineering.* 7th edn. ed.: Chris Carson.

David, T. K., Chandrasegaran, R. S. and Nair, S. K. 2018. Modified Pervious Concrete Containing Recycled Asphalt Pavement and Waste Tire Rubber. *IOP Conference Series: Materials Science and Engineering,* 371, 012011.

Day, G. E., Smith, D. R. and Powers, J. N., 1981. *Runoff and pollution abatement characteristics of concrete grid pavements.* Blacksburg: Virginia Water Resources Center, Virginia Polytechnic and State University.

Deng, Y. and Wheatley, A. 2018. Mechanisms of Phosphorus Removal by Recycled Crushed Concrete. *International Journal Environmental Research and Public Health,* 15(2), 16.

Dhir, R. K. and Jackson, N., 1996. Concrete. *In:* Jackson, N. and Dhir, R. K. eds. *Civil Engineering Materials.* 5th ed. New York, USA: Palgrave.

Drake, J., Bradford, A. and Marsalek, J. 2013. Review of environmental performance of permeable pavement systems: state of the knowledge. *Water Quality Research Journal of Canada,* 48(3), 203–222.

Drake, J., Bradford, A. and Van Seters, T. 2014a. Hydrologic performance of three partial-infiltration permeable pavements in a cold climate over low permeability soil. *Journal of Hydrologic Engineering,* 19(9), 04014016.

Drake, J., Bradford, A. and Van Seters, T. 2014b. Stormwater quality of spring–summer-fall effluent from three partial-infiltration permeable pavement systems and conventional asphalt pavement. *Journal of Environmental Management,* 139, 69–79.

EN 197-1, 2011. Cement - Part 1: Composition, specifications and conformity criteria for common cements. Brussels, Belgium: CEN.

Fassman, E. A. and Blackbourn, S. 2010. Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering,* 15(6), 475–485.

Ferguson, B. K., 2005. Why Make Pavements Porous? *Porous Pavements.* Boca Raton, Fl, USA: CRC Press.

Garach, L.*, et al.* 2015. Improvement of Bearing Capacity in Recycled Aggregates Suitable for Use as Unbound Road Sub-Base. *Materials,* 8(12), 8804–8816.

Geosyntec Consultants and Wright Water Engineers, I., 2009. *Urban Stormwater BMP Performance Monitoring Manual.* Washington, D.C., USA: US EPA, WERF, FHWA, ASCE-EWRI.

Gilbert, J. K. and Clausen, J. C. 2006. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. *Water Research,* 40(4), 826–832.

GoRTT, 2018. *Oil and Gas Industry* [online]. Available from: http://www.energy.gov.tt/our-business/oil-and-gas-industry/ [Accessed 24 May 2019].

Hammer, M. J. and Hammer Jr., M. J., 2007. *Water and wastewater technology.* 6th ed. ed. New Jersey: Pearson.

Hein, D. K., 2014. Permeable Pavement Design and Construction Case Studies in North America. *2014 Conference and Exhibition of the Transportation Association of Canada.* Montreal, Quebec, Canada, 1–12.

Holmes, R. R., Hart, M. L. and Kevern, J. T. 2017. Enhancing the ability of pervious concrete to remove heavy metals from stormwater. *Journal of Sustainable Water in the Built Environment,* 3(2), 04017004.

IBM, 2011. IBM SPSS statistics for Windows, version 20.0. New York, USA: IBM Corp.

ICPI, 2016. *Permeable Pavers* [online]. Available from: https://www.icpi.org/paving-systems/permeable-pavers [Accessed 10 September 2016].

IDB, 2018. *Development Challenges in the Caribbean.* Washington, D.C., USA: Inter-American Development Bank (IDB).

Interpave, 2018. *Design & Construction of Concrete Block Permeable Pavements.* 7th Ed. ed. Leicester, UK: Interpave.

Inyang, H. I. 2003. Framework for Recycling of Wastes in Construction. *Journal of Environmental Engineering,* 129(10), 887–898.

James, W. and Shahin, R. 1998. A Laboratory Examination of Pollutants Leached from Four Different Pavements by Acid Rain. *Journal of Water Management Modeling,* 200(17), 321–349.

Jamshidi, A., *et al.* 2016. Performance of pavements incorporating waste glass: The current state of the art. *Renewable and Sustainable Energy Reviews,* 64(Supplement C), 211–236.

Jamshidi, A., *et al.* 2019. State-of-the-art of interlocking concrete block pavement technology in Japan as a post-modern pavement. *Construction and Building Materials,* 200, 713–755.

Jang, J. G., *et al.* 2015. A novel eco-friendly porous concrete fabricated with coal ash and geopolymeric binder: Heavy metal leaching characteristics and compressive strength. *Construction and Building Materials,* 79, 173-181.

Jato-Espino, D., *et al.* 2016. Coupling GIS with stormwater modelling for the location prioritization and hydrological simulation of permeable pavements in urban catchments. *Water,* 8(10), 451.

Jayakaran, A. D., *et al.* 2019. Remediation of Stormwater Pollutants by Porous Asphalt Pavement. *Water,* 11(3), 520.

Jindal, A. and Ransinchung, G. D. 2018. Behavioural study of pavement quality concrete containing construction, industrial and agricultural wastes. *International Journal of Pavement Research and Technology,* 11(5), 488-501.

Kan, A. and Demirboğa, R. 2009. A novel material for lightweight concrete production. *Cement and Concrete Composites,* 31(7), 489–495.

Kaya, A. and Kar, F. 2016. Properties of concrete containing waste expanded polystyrene and natural resin. *Construction and Building Materials,* 105, 572–578.

Kazemi, F. and Hill, K. 2015. Effect of permeable pavement basecourse aggregates on stormwater quality for irrigation reuse. *Ecological Engineering,* 77, 189–195.

Khankhaje, E.*, et al.* 2017. Comparing the effects of oil palm kernel shell and cockle shell on properties of pervious concrete pavement. *International Journal of Pavement Research and Technology,* 10(5), 383–392.

Kim, G. M.*, et al.* 2017. Water purification characteristics of pervious concrete fabricated with CSA cement and bottom ash aggregates. *Construction and Building Materials,* 136, 1-8.

Lalla, J. R. F. and Mwasha, A. 2014. Investigating the Compressive Strengths of Guanapo Recycled Aggregate Concrete as Compared to that of its Waste Material. *West Indian Journal of Engineering,* 36(2), 12–19.

Li, H.*, et al.* 2017. The effect of different surface materials on runoff quality in permeable pavement systems. *Environmental Science and Pollution Research,* 24(26), 21103–21110.

Lucke, T. and Beecham, S. 2011. Field investigation of clogging in a permeable pavement system. *Building Research & Information,* 39(6), 603–615.

Martinho, F. C. G., Picado-Santos, L. G. and Capitão, S. D. 2018. Feasibility Assessment of the Use of Recycled Aggregates for Asphalt Mixtures. *Sustainability,* 10(6), 1737.

McHardy, P. and Donovan, M. G., 2016. *The State of Social housing in Six Caribbean Countries.* Washington, D.C., USA: Inter-American Development Bank (IDB).

Miron, L. E. R. D. and Magaña, M. E. L., 2017. Chapter 2 Influence of Sulfur Ions on Concrete Resistance to Microbiologically Induced Concrete Corrosion. *In:* Miron, L. E. R. D. and Koleva, D. A. eds. *Concrete Durability.* New York: Springer International Publishing, 162.

Monrose, J. and Tota-Maharaj, K. 2018. Technological Review of Permeable Pavement Systems for Applications in Small Island Developing States. *CLEAN – Soil, Air, Water,* 46(9), 1700168.

Monrose, J.*, et al.* 2019. Effect of carbon-negative aggregates on the strength properties of concrete for permeable pavements. *International Journal of Pavement Engineering*, 1-9.

Murugan, R. B., Natarajan, C. and Chen, S.-E. 2016. Material development for a sustainable precast concrete block pavement. *Journal of Traffic and Transportation Engineering (English Edition),* 3(5), 483-491.

Mwasha, A., Armstrong-Richardson, A. and Wilson, W. 2013. Management of Polystyrene Wastes Using a Supercritical Solvent - Propanone. *The Journal of Association of Professional Engineers of Trinidad and Tobago,* 41(1), 23–28.

Myers, B., Beecham, S. and Leeuwen, J. A. v. 2011. Water quality with storage in permeable pavement basecourse. *Proceedings of the Institution of Civil Engineers - Water Management,* 164(7), 361–372.

Myers, B. R*., et al.* 2009. Depletion of E. coli in permeable pavement mineral aggregate storage and reuse systems. *Water Science and Technology,* 60(12), 3091–3099.

Ngugi, H. N., Kaluli, J. W. and Abiero-Gariy, Z. 2017. Use of expanded polystyrene technology and materials recycling for building construction in Kenya. *American Journal of Engineering Technology Management,* 2(5), 41-50.

Nishigaki, M. 2000. Producing permeable blocks and pavement bricks from molten slag. *Waste Management,* 20(2–3), 185–192.

Nnadi, E. O*., et al.* 2014. An evaluation of enhanced geotextile layer in permeable pavement to improve stormwater infiltration and attenuation. *International Journal of Pavement Engineering,* 15(10), 925–932.

Nnadi, E. O*., et al.* 2015. Stormwater harvesting for irrigation purposes: An investigation of chemical quality of water recycled in pervious pavement system. *Journal of Environmental Management,* 147, 246–256.

Orlov, V., Martynov, S. and Kunytskiy, S. 2016. Energy saving in water treatment technologies with polystyrene foam filters. *Journal of Water and Land Development,* 31(1), 119.

Osuagwu, J. C., Nwakwasi, N. L. and Nwachukwu, A. N. 2018. Iron removal in waste water using expanded polystyrene as an artificial media. *Nigerian Journal of Technology,* 37(3), 841-845.

Pagotto, C., Legret, M. and Le Cloirec, P. 2000. Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Research,* 34(18), 4446–4454.

Parkinson, J. 2002. Urban drainage in developing countries – challenges and opportunities. *Waterlines,* 20(4), 2–5.

Pilon, B. S*., et al.* 2019. The Effect of Pervious Concrete on Water Quality Parameters: A Case Study. *Water,* 11(2), 263.

Poon, C. and Chan, D. 2006. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials,* 20(8), 578–585.

Pratt, C. J., 1997. Design guidelines for porous/permeable pavements. *In:* Rowney, C. ed. *Engineering Foundation Conference: Sustaining Water Resources in the 21st Century.* Malmö, Sweden: ASCE.

Pratt, C. J., Mantle, J. D. G. and Schofield, P. A. 1995. UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality. *Water Science and Technology,* 32(1), 63–69.

Rahman, M. A.*, et al.* 2014. Suitability of recycled construction and demolition aggregates as alternative pipe backfilling materials. *Journal of Cleaner Production,* 66, 75–84.

Rahman, M. A.*, et al.* 2015a. Engineering and Environmental Assessment of Recycled Construction and Demolition Materials Used with Geotextile for Permeable Pavements. *Journal of Environmental Engineering,* 141(9), 04015019.

Rahman, M. A.*, et al.* 2015b. Recycled construction and demolition materials in permeable pavement systems: geotechnical and hydraulic characteristics. *Journal of Cleaner Production,* 90, 183–194.

Rao, A., Jha, K. N. and Misra, S. 2007. Use of aggregates from recycled construction and demolition waste in concrete. *Resources, Conservation and Recycling,* 50(1), 71–81.

Razzaghmanesh, M. and Borst, M. 2019. Long-term effects of three types of permeable pavements on nutrient infiltrate concentrations. *Science of the Total Environment,* 670, 893–901.

Reddy, K. R., Xie, T. and Dastgheibi, S. 2014. Removal of heavy metals from urban stormwater runoff using different filter materials. *Journal of Environmental Chemical Engineering,* 2(1), 282–292.

Rizvi, R.*, et al.* 2010. Evaluating the use of recycled concrete aggregate in pervious concrete pavement. *Transportation Research Record: Journal of the Transportation Research Board,* (2164), 132–140.

Rodriguez-Hernandez, J.*, et al.* 2015. Laboratory Study on the Stormwater Retention and Runoff Attenuation Capacity of Four Permeable Pavements. *Journal of Environmental Engineering,* 142(2), 04015068.

Rodríguez-Rojas, M. I., *et al.* 2018. A study of the application of permeable pavements as a sustainable technique for the mitigation of soil sealing in cities: A case study in the south of Spain. *Journal of Environmental Management,* 205, 151–162.

Sansalone, J., *et al.* 2012. Filtration and clogging of permeable pavement loaded by urban drainage. *Water Research,* 46(20), 6763-6774.

Sañudo-Fontaneda, L. A., *et al.* 2014. Water quality and quantity assessment of pervious pavements performance in experimental car park areas. *Water Science and Technology,* 69(7), 1526–1533.

Sawyer, C. N., McCarty, P. L. and Parkin, G. F., 2003. *Chemistry for Environmental Engineering and Science.* 5th Ed. ed. New York: McGraw-Hill.

Scholz, M. 2013. Water quality improvement performance of geotextiles within permeable pavement systems: A critical review. *Water,* 5(2), 462–479.

Scholz, M. and Grabowiecki, P. 2007. Review of permeable pavement systems. *Building and Environment,* 42(11), 3830–3836.

Schöntag, J. M., *et al.* 2015. Water quality produced by polystyrene granules as a media filter on rapid filters. *Journal of Water Process Engineering,* 5(Supplement C), 118–126.

Selvakumar, A. and O'Connor, T. P. 2018. Organism Detection in Permeable Pavement Parking Lot Infiltrates at the Edison Environmental Center, New Jersey. *Water Environment Research,* 90(1), 21–29.

Siriwardene, N. R., Deletic, A. and Fletcher, T. D. 2007. Clogging of stormwater gravel infiltration systems and filters: Insights from a laboratory study. *Water Research,* 41(7), 1433–1440.

Sokolović, R. S., Sokolović, S. and Govedarica, D. 2009. Performance of expanded polystyrene particles in deep bed filtration. *Separation and Purification Technology,* 68(2), 267–272.

Sounthararajah, D. P., *et al.* 2017. Removing heavy metals using permeable pavement system with a titanate nano-fibrous adsorbent column as a post treatment. *Chemosphere,* 168, 467–473.

Tam, V. W. Y. 2009. Comparing the implementation of concrete recycling in the Australian and Japanese construction industries. *Journal of Cleaner Production,* 17(7), 688-702.

Tatsuoka, F., *et al.* 2013. Strength and stiffness of compacted crushed concrete aggregate. *Soils and Foundations,* 53(6), 835–852.

Tavares, L. M. and Kazmierczak, C. S. 2016. The influence of recycled concrete aggregates in pervious concrete. *Revista IBRACON de Estruturas e Materiais,* 9(1), 75–89.

Thelen, E., *et al.*, 1972. *Investigation of porous pavements for urban runoff control.* Washington, D.C.: Environmental Protection Agency, Office of Research and Monitoring.

Tota-Maharaj, K., 2010. *Geothermal paving systems for urban runoff treatment and renewable energy efficiency.* Thesis (PhD). The University of Edinburgh.

Tota-Maharaj, K., *et al.*, 2012. The performance and effectiveness of geotextiles within permeable pavements for treating concentrated stormwater. *Sixteenth International Water Technology Conference, IWTC 16.* Istanbul, Turkey 1–13.

Tota-Maharaj, K. and Scholz, M. 2010. Efficiency of permeable pavement systems for the removal of urban runoff pollutants under varying environmental conditions. *Environmental Progress & Sustainable Energy,* 29(3), 358–369.

US EPA, 2012. *Guidelines for Water Reuse.* Washington, D.C.: CDM Smith Inc.

Vadas, T. M., Smith, M. and Luan, H. 2017. Leaching and retention of dissolved metals in particulate loaded pervious concrete columns. *Journal of Environmental Management,* 190, 1–8.

Wang, X., *et al.* 2014. Sequestration of phosphorus from wastewater by cement-based or alternative cemetitious materials. *Water Research,* 62, 88–96.

Weiss, P. T., *et al.* 2017. Permeable pavement in northern North American urban areas: research review and knowledge gaps. *International Journal of Pavement Engineering*, 1–20.

Xu, Y., *et al.* 2012. Mechanical properties of expanded polystyrene lightweight aggregate concrete and brick. *Construction and Building Materials,* 27(1), 32–38.

Yao, X., *et al.* 2019. Synergistic use of industrial solid waste mixtures to prepare ready-to-use lightweight porous concrete. *Journal of Cleaner Production,* 211, 1034-1043.

Zhang, Z., *et al.* 2018. Systematically Investigated the Influences of Permeable Pavement Materials on the Water Quality of Runoff: Batch and Column Experiments. *Water, Air, & Soil Pollution,* 229(5), 155.