Suitability of reclaimed asphalt pavement and recycled crushed brick as filter media in bioretention applications

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Abstract: Bioretention systems are increasingly being used in urban stormwater management systems, whereas quarry materials are used as filter media; however the use of quarry materials in this application reduces valuable natural resources. Such a novel approach of using recycled waste materials would significantly conserve valuable natural resources. A series of laboratory tests included particle size distribution, organic content, pH, specific gravity, flakiness index and hydraulic conductivity. Among the pollutants, total suspended solid (TSS), total phosphorus (TP) and total nitrogen (TN) were selected. A model for bioretention system was simulated to investigate the effectiveness of reclaimed asphalt material (RAP) and crushed brick (CB) materials in trapping selected pollutants. In terms of physical and chemical properties, RAP and CB were found to meet the stringent requirements of various environmental protection authorities. This research further indicates that recycled waste materials can be reused viably as alternative materials in bioretention systems.

Keywords: bioretention; crushed brick; MUSIC; permeability; pollutant; reclaimed asphalt material; RAP.

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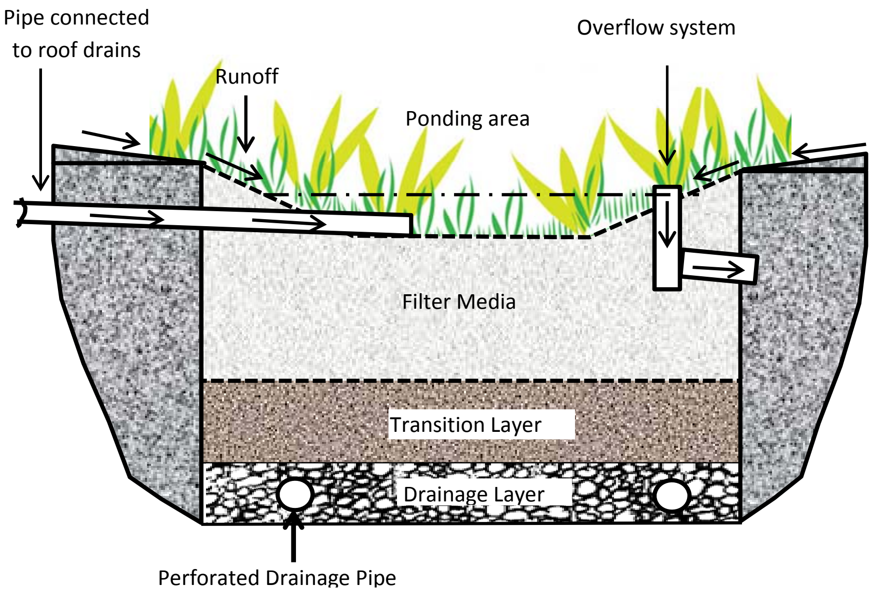
1 Introduction

With rapid industrialisation and population growth, large amounts of land are being used in various infrastructures such as roads, footpaths and parking lots in both urban and rural areas. These days, it is also important to also design and manage the surrounding areas of these infrastructures in such a way that it can reduce runoff, as well as pollutants that are transported during storm events. Urban runoff is one of the main causes of pollution and hence stormwater management is an increasing priority worldwide. At the same time, stream ecosystems are also being degraded in various ways which are very difficult to distinguish, such as lowering of groundwater levels, increasing frequency and intensity of flood flows, loads of pollutants and stream bank erosion with multiple impacts on aquatic ecosystems (Novotny and Olem, 1994; Paul and Meyer, 2001). Increases of imperviousness in urban areas also results in uncontrolled stormwater (Novotny and Olem, 1994). That is harmful to receiving water in urban waterways. It is therefore required to manage the quality and quantity of urban runoff to protect and restore the ecological health in urban waterways. Laboratory studies on the reduction of heavy metals, phosphorus, ammonium and other pollutants have been conducted previously (Davis, 2006; Fletcher et al., 2007). Hatt et al. (2006) also investigated the leaching characteristics of nitrogen and phosphorus through non-vegetated filter media. Henderson et al. (2007) investigated the performance of three different filter media (gravel, sand and sandy loam) in vegetated and non-vegetated columns, in which vegetated columns removed more nitrogen and phosphorus than non-vegetated columns. In addition to water quality benefits, bioretention systems also help to reduce flood peak and volume (Hunt, 2003).

The negative impacts of urban stormwater runoff are widely recognised among various end-users and as such, two important goals being regulating stormwater quantity and quality are essential for its proper management (Meyer et al., 2005). A number of stormwater water treatment technologies such as constructed wetlands, sedimentation ponds, sand filters and infiltration systems have been previously developed (Davis, 2006). Bioretention system (also known as rain gardens and biofilters) is a technique used to capture and infiltrate as much as stormwater from impervious surfaces such as roads, parking lots and roofs. These bioretention systems control pollutants by filtering distracted stormwater runoff through vegetation followed by vertical filtration into filter media. Schematic diagram of a typical bioretention system is shown in Figure 1. The treatment process is obtained through different systems such as sedimentation, sorption fine filtration and biological uptake (PGC, 2002). The water is then discharged through the under-drains of the filter media to the drainage system or waterways. If the filter media is not properly designed, the intension to trap various pollutants and heavy metals are difficult to achieve. Therefore, it is required to design the filter media accurately in order to reduce pollutants and heavy metals in urban waterways.

Figure 1 Schematic diagram of a typical bioretention system (see online version for colours)



Melbourne is the capital of the state of Victoria, Australia. The Victorian state government has put into effect a zero-waste policy directive in which all wastes, regardless of quantity, should be diverted from landfill. Challenges of low-carbon economies and resource depletion are major factors in pushing toward reuse of construction and demolition (C&D) materials in roadwork applications (DSEWPC, 2012). The extensive amount of waste generated by various industries and human activities has made a major problem for the disposal of solids waste in Victoria, as well as around the world. In Australia, approximately 8.7 million tons of demolition concrete, 1.3 million tons of demolition brick, 3.3 million tons of waste excavation rock, 1.0 million tons of waste glass and 1.2 million tons of reclaimed asphalt pavements are stockpiled annually and these stockpiles are growing radically (Sustainability Victoria, 2010). A similar trend exists around the world in all developed and developing countries.

The state road and water authorities in Australia are currently exploring the potential reuse option for C&D materials in various civil engineering applications (EPA Victoria, 2009; VicRoads, 2007). The sustainable usages of waste materials in stormwater and geotechnical engineering applications have considerable social and economic benefits to industrialised and developing nations. Simultaneously, shortages of natural mineral resources and increasing waste disposal costs have brought added significance to the recycling and reusing of C&D wastes in recent years (Landris, 2007; Arulrajah et al., 2014; Rahman et al., 2014a, 2014b). The engineering properties of various waste aggregates used as alternative construction materials in various developed and developing countries have also been reported by several authors (Kartam et al., 2004). Other waste materials that have generated recent interests in various geotechnical applications include waste glass (Imteaz et al., 2012), municipal solid waste (Zekkos et al., 2010) and waste excavation rock in pavement sub-base applications (Tsang et al., 2005). These reports suggest that reusing C&D waste in most cases are cost-effective solutions compared to using natural virgin aggregate (DSEWPC, 2012). In addition to potential cost savings, there are also significant carbon savings in the usage of recycled materials in civil engineering applications. A comparison of the properties of C&D materials is required for uses in bioretention systems as this is gaining importance to consultants, contractors, designers, local councils, state water authorities, operators and end-users alike in their potential usage in water engineering applications.

An attempt has been made in this research to encourage reuse of recycled materials as bioretention filter media in urban storm water management. The hydrologic and pollutant removal performances of stormwater bioretention systems in urban catchments have been established by Hatt et al. (2009). The hydraulic behaviour of recycled materials in bioretention systems has however not yet been established to date and furthermore, there is also a lack of information on the treatment performance of recycled materials in bioretention systems. The present study investigates the hydraulic performance and pollutants removal efficiency of bioretention systems using recycled materials such as RAP and CB. Another attempt has also been made in this research to compare evaluated properties of RAP and CB with various physical, geotechnical and hydraulic properties recommended by different regulatory authorities in regards to bioretention system.

2 Methodology

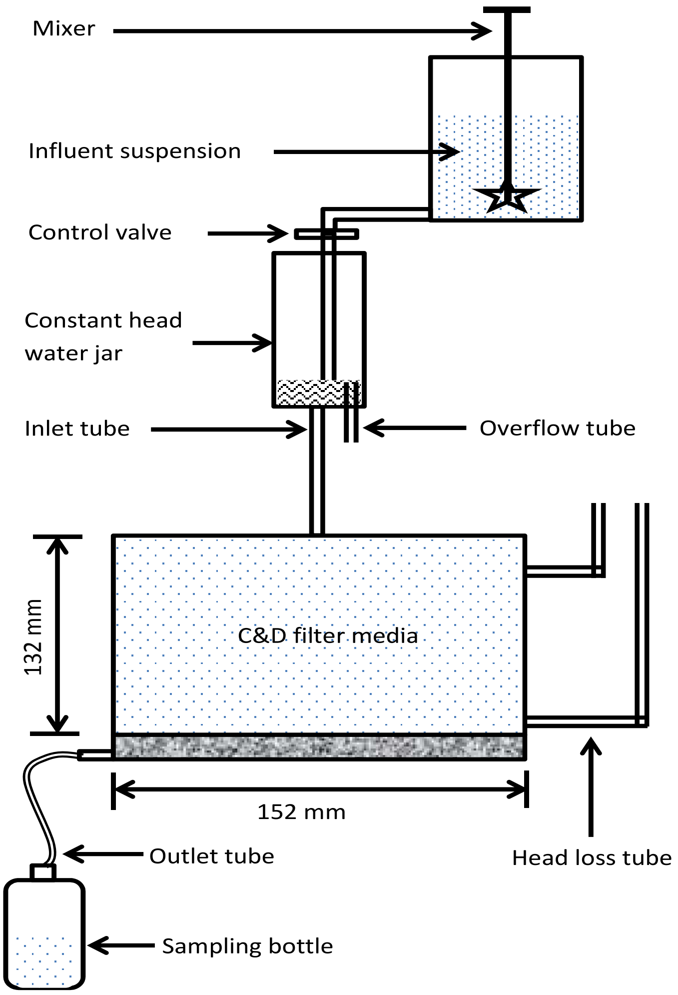
Recycled C&D materials (RAP and CB) were collected from a recycling site in the state of Victoria, Australia. The samples were first oven dried and subsequently different laboratory tests were undertaken on the recycled aggregates targeting their usage as alternative filter materials in urban stormwater bioretention systems. Physical, geotechnical and hydraulic properties were subsequently analysed in this research.

2.1 Physical properties testing

Particle size distribution tests of the C&D materials were conducted according to ASTM-D422-63 (2007). The particle size distribution targeted between lower and upper bound reference lines for aggregates in backfilling, filter media, sub-base and other civil engineering applications. Initially the samples were washed with distilled water through a sieve size of 75 µm. The retained samples were taken and dried for 24 hours before further sieve analysis tests. Specific gravity and water absorption tests of coarse aggregate (retained on 4.75 mm sieve) and fine aggregate (passed through 4.75 mm sieve) were undertaken according to ASTM-C127 (2007).

The pH tests were performed in accordance with BS 1377 (1990). About 30 g of dry sample, which passed through a 200 µm sieve, was taken and 75 ml of distilled water was added to the sample and stirred for a few minutes before suspension was left standing overnight. The suspension was stirred immediately before testing. The pH value of the suspension was measured by a digital device. The loss of ignition method was used to determine the organic content of the aggregates (ASTM-D2974, 2007). To determine the maximum dry density and optimum moisture content, modified compaction tests were performed on the recycled materials (ASTM-D1557, 2009). Flaky characteristics of the materials were determined using flakiness index test according to BS 812-105.1 (2000).

Figure 2 Schematic diagram of laboratory testing setup for permeability testing



2.2 Permeability testing

A laboratory test setup of constant head permeability testing apparatus was used in this research for determining the coefficient of hydraulic conductivity of the C&D materials. A schematic diagram of the hydraulic conductivity testing apparatus is shown in Figure 2. The main cylinder of the hydraulic conductivity testing apparatus had an internal diameter of 152 mm and a height of 132 mm. Coustumer et al. (2008) used a cylinder having 100 mm diameter and 85 mm height for their laboratory tests. The C&D materials were selected between the lower and upper bound limits as per the state water and road authority's requirements to allow sufficient infiltration through the media. The hydraulic conductivity tests were performed for coarse grained C&D materials in accordance with ASTM-D2434-68 (2006). For the determination of hydraulic conductivity, the constant head method was used for granular C&D materials used in this research.

2.3 Pollutant removal testing

The influent solutions were prepared in the laboratory by adding pollutants with distilled water to achieve a total suspended solids (TSS) concentration of approximately 250 mg/L as worst case scenario. This was slightly higher than the average TSS concentrations in stormwater runoff events occurring in urban areas (Kim and Sansalone, 2008; Li and Davis, 2008). Several researchers (i.e., Hatt et al., 2005; Clark and Pitt, 2009) had investigated reductions in sediment concentrations through various filter media such as sand, carbon sand, peat sand and composed sand.. In this research, water samples were collected at the inflow and outflow of the C&D filter media. Subsequently, the water samples were analysed for TSS, total nitrogen (TN) and total phosphorus (TP) using standard methods (Standard Methods, 1998). Only these three pollutants (TSS, TN and TP) were selected as the mathematical model (MUSIC) with which was developed to simulate pollutants trapping efficiencies can calculate only these three pollutants in addition to gross pollutants.

Wong et al. (2002) developed the Model for Urban Stormwater Improvement Conceptualisation (MUSIC). MUSIC provides the ability to simulate both quantity and quality of runoff from urban and rural areas. One of the great strengths of MUSIC is the ability to model the treatment processes that occur with stormwater treatment devices (Wong et al., 2006). MUSIC enables users to evaluate conceptual design of stormwater management systems to ensure they are appropriate for their catchments and are expected to achieve specified water quality objectives. MUSIC's simulations can be based on event or continuous basis, which allows rigorous analysis and comparisons between short-term and long-term benefits of any stormwater treatment system. MUSIC Version 3.0 can simulate treatment efficiencies for buffer strip, vegetated swale, bioretention system, wetland, infiltration system, pond, sedimentation basin, rainwater tank and gross pollutant traps. MUSIC is currently one of the most popular models used by Australian industries in predicting the performance outcomes for various WSUD techniques. MUSIC has been used in some other countries as well. Imteaz et al. (2013) tested MUSIC for different treatment systems in Brisbane, Melbourne, Sweden, Auckland and Scotland. Their findings were quite varying; in some cases it was found to overestimate the stormwater treatment systems capacity and on the other hand in some other cases it underestimated the treatment capacity. In general, MUSIC's predictions for flow and TSS removals were close to measurements, whereas in some cases predictions of TP and TN removals were overestimated.

In terms of bioretention applications, initially the MUSIC software was validated for ‘porous pavement’ system, which used filter media only without biological actions (i.e., without plants/shrubs). The validated model was then converted to bioretention model keeping the individual filter media properties of each C&D material. Different C&D materials were represented by their relevant hydraulic conductivity values (obtained thorough laboratory experiments) in MUSIC program. Developed MUSIC models simulated various treatment efficiencies through bioretention systems in regards to TSS, TN and TP. As MUSIC required rainfall data; a random SIX minutes interval recorded rainfall series from the year 1959 was selected for this purpose. The MUSIC’s default parameters regarding inflow pollutants concentrations were adjusted to generate the same influent pollutants concentrations used in the experiments.

3 Results and discussions

The physical, geotechnical, hydraulic and chemical properties of the C&D materials in urban bioretention applications and comparison with typical specified requirements are presented in the following sections.

Table 1 Physical and geotechnical properties of C&D materials

Physical properties	*CB*	*RAP*	*Typical requirements (VicRoads, 2010)*
Specific gravity – coarse	2.41	2.34	> 2.0
Specific gravity – fine	2.48	2.33	> 2.0
Organic content (%)	2.02	4.03	< 5.0
pH	9.50	7.20	6–11
Compaction (modified): MDD (kN/m^3)	20.40	19.40	> 17.50
Compaction (modified): OMC (%)	12.75	8.30	8–15
USCS classification	GW	GW	GW/SW
ASCS classification	GP-GM	GP	GW/SW
AASHTO classification	A-1-a	A-1-a	A-1-a

3.1 Physical properties

Physical properties of the C&D materials were conducted from three replicate samples for each test to maintain consistency of the results. Specific gravity values of CB and RAP were found to meet typical requirements specified by state water and road authorities. The specific gravity for RAP was however found to be slightly lower than CB materials. The specific gravity results for the C&D materials indicated that they can be considered high quality aggregates. It can also be seen from Table 1 that the specific gravity values of coarse aggregates were slightly higher than those of the fine aggregates for all the tested materials used in this research. The organic content of the C&D materials was found to be low except for RAP, which was also found in the acceptable ranges. Several researchers had found that the typical organic content values of biofilter

filter media were between 0–10% as shown in Table 2 (Woods-Ballart et al., 2007; FAWB, 2009).

Table 2 Comparisons between present study and existing guidelines of bioretention filter materials properties

Guideline	*Aggregate*	*Organic content*	*Remarks*
Present study	Sand-gravel (38–56%)	2–4%	2–9% fine content
ARC (2003)	Sandy loam (35–60%)	Not specified	Clay content < 25%
PGC (2007) Meryland	35–60% sand	20–30% well aged leaf compost	Clay content < 5%
The SUDS manual (Woods-Ballart et al., 2007)	35–60% sand, 30–50% silt	0–4% organic content	10–25% clay content
Facility for advance water biofiltration (FAWB, 2009)	Washed, well graded sand with specified PSD band	3–10% organic content	Clay content < 3%
North Carolina cooperative extension service (Hunt and Lord, 2006)	85–88% washed medium sand	3–5% organic content	8–12% silt and clay
City of Austin (2011)	70–80% concrete sand	20–30% screened bulk topsoil	3–10% clay content

The pH value of the C&D materials indicated those materials were slightly alkaline, though within expected limits of 6–11. The pH value for natural soils and soil blends that can be used as biofilter media was 5.5–7.5, according to FAWB (2009) requirements. The flakiness index value was within the upper limit of 35; typically specified for backfilling, bioretention filter media and permeable pavement sub-base materials. Table 1 also shows the results of modified compaction tests conducted on the recycled C&D materials. The modified compaction results indicated that CB had the highest MDD, while RAP had the lowest due to the presence of bitumen substances with RAP. The OMC of the C&D materials indicated that RAP had the lowest OMC of 8.30%, while CB had the highest of 12.75%.

The gradation curves of the C&D materials are shown in Figure 3 and compared with the state road and water authorities' specifications for the usage of quarried materials in urban stormwater management systems. Soil classification symbols from the Australian Soil Classification System (ASCS), the Unified Soil Classification System (USCS) and AAHOTO systems are also presented in Table 1. According to the ASCS, the C&D materials had approximately equal amounts of sand and gravel sized fractions, enabling them to be classified as well-graded gravel (GW). Based on the gradation curves, the grain size distribution parameters including D_{90}, D_{10}, C_u and C_c are summarised in Table 3. The comparison between C&D materials and drainage applications requirements is also shown in Table 3 (Drainage Factsheet, 2000). The soil classification results showed all those parameters were meeting the drainage filter media requirements. Therefore, the C&D materials used in this research were suitable for bioretention filter media in stormwater management systems. The results showed that the tested RAP and CB aggregates were consistent with the requirements of typical aggregates for civil engineering applications such as bioretention filter materials, permeable pavement subbases, footpaths and back filling purposes.

Figure 3 Particle size distribution and comparisons of the C&D materials

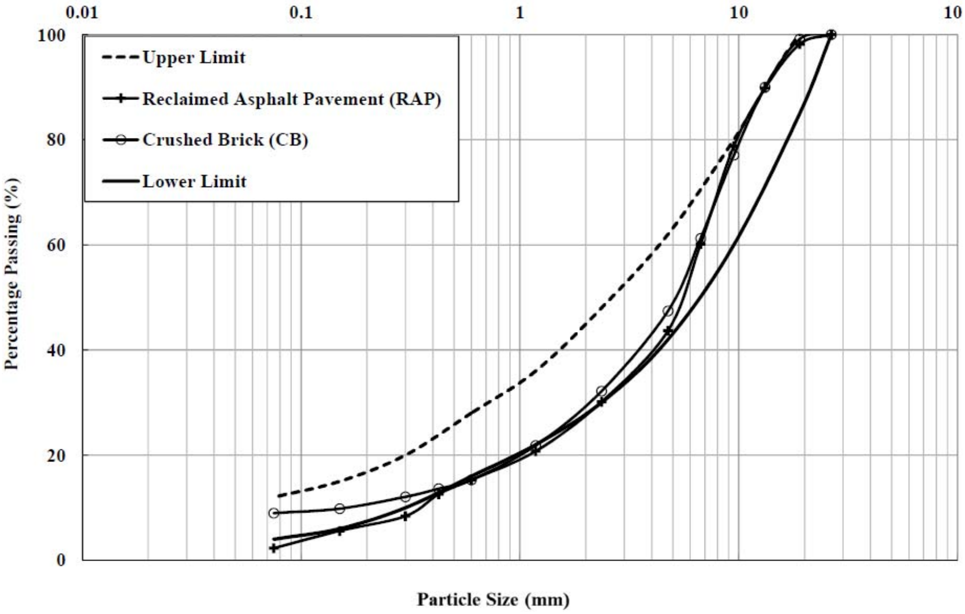


Table 3 Typical requirements and comparisons for well graded filter materials

Properties	*Present study*	*Typical requirements (Drainage Factsheet, 2000)*
Maximum size	19 mm	38 mm
D_{90}	12–15 mm	≤ 19 mm
D_{10}	0.19–0.85 mm	≥ 0.25 mm
C_u	7.8–71.0	Gravel, $C_u > 6$; sand > 4
C_c	1.80–2.80	$1 \leq C_c \leq 3$

3.2 Permeability results analysis

Constant head permeability testing of the C&D materials was undertaken in this research. Table 4 shows the hydraulic behaviour of the C&D materials used in this research. Among the tested C&D materials, hydraulic conductivity was higher for RAP compared to CB. The hydraulic conductivity values were found to be within the range of those specified for the usage of aggregates in bioretention filter media and permeable pavement sub-base applications in urban stormwater management system (Melbourne Water, 2005). Table 4 also shows the comparison of hydraulic conductivities between present study and published guidelines (CASQA, 2003; City of Austin, 2011; EPA US 2004; FAWB, 2009; PGC, 2007; Woods-Ballart et al., 2007; Hunt and Lord, 2006). The permeability results obtained from present study satisfied the requirements to use in bioretention filter media according to mentioned guidelines. Therefore, authors recommend that the particular RAP and CB materials used in this research can be used as filter materials in stormwater management systems.

Table 4 Comparisons between present study and existing guidelines of hydraulic conductivity for bioretention filter materials

Guideline	*Hydraulic conductivity (mm/h)*
Present study	47–124
California bioretention TC-32 (CASQA, 2003)	12.50
City of Austin (2011)	50.80
EPA US (2004)	12.70
FAWB (2009)	50–300
PGC, Meryland (2007)	12.70
The SUDS manual (Woods-Ballart et al., 2007)	12.60
North Carolina cooperative extension service (Hunt and Lord, 2006)	25.4 (for nitrogen removal), 50.80 (for phosphorus, metal and other pollutant removal)

3.3 Pollutant removal efficiency

Pollutant removal efficiencies of the C&D materials were assessed in this research to investigate the suitability of these materials as filter media in bioretention systems. The laboratory results and MUSIC modelling were compared with the previous guidelines and case studies. Kaolinite fine solid particles and distilled water were used to prepare influent suspension. Chemical tests of the inflow and outflow samples were carried out in an accredited commercial environmental laboratory, Australian Laboratory Services (http://www.alsglobal.com/). Series of laboratory experiments were conducted to assess pollutants removal efficiencies of permeable pavement systems using C&D materials. Later MUSIC models were developed and calibrated with the experimental results. Three different water quality parameters namely TSS, TN and TP were assessed and compared in this research. Rahman et al. (2014c) provided details of comparison with experimental results and calibration of MUSIC models. In general MUSIC models' simulations were reasonable.

Table 5 Comparisons of TSS removal efficiencies for bioretention systems between present study and existing guidelines

Site name	*Influent concentration (mg/L)*	*Effluent concentration (mg/L)*	*Load reduction (%)*	*Study cases*
MUSIC modelling	250	21–45	82–92	Present study
Laboratory columns	150	107	27	Hsieh and Davis (2005)
College Park	34	18	59	Davis (2007)
Charlotte, N.C.	49.5	20	60	Hunt et al. (2008)
Durham, N.H.	--	--	97	UNHSC (2006)
Field study	--	--	79–97	Carpenter and Hallam (2010)

Bioretention system uses similar filter media as permeable pavements, having some specific shrubs on top of it. Root system of the grown shrubs provides additional treatment. As such, in regards to pollutants removal efficiency, bioretention system is better than the permeable pavement system having same filter media. Table 5 shows the results of TSS removal efficiencies from the present study and comparison with other studies and guidelines (Hsieh and Davis, 2005; UNHSC, 2006; Davis, 2007; Hunt et al., 2008; Carpenter and Hallam, 2010). From the presented comparison, as the simulated pollutant removal efficiencies of the C&D materials were higher than typical requirements, it can be used as filter materials in bioretention systems.

Table 6 Comparisons of TN removal efficiencies for bioretention filter materials between present study and existing guidelines

Site name	*Influent concentration (mg/L)*	*Effluent concentration (mg/L)*	*Load reduction (%)*	*Study cases*
MUSIC modelling	2.8	0.78–1.15	59–72	Present study
Laboratory columns	2.1	0.1–3	95	Kim and Sansalone (2008)
Greensboro, N.C.	1.35	4.38	40	Hunt et al. (2006)
Louisburg, N.C.	1.70	1.25	65	Sharkey (2006)
Pilot boxes	1.6–6.0	1.1–2.8	30–99	Davis et al. (2006)
Haddam, Conn.	1.2	0.8–1.0	32	Dietz and Clausen (2006)

Table 7 Comparisons of TP removal efficiencies for bioretention filter materials between present study and existing guidelines

Site name	*Influent concentration (mg/L)*	*Effluent concentration (mg/L)*	*Load reduction (%)*	*Study cases*
MUSIC modelling	2.24	0.52–0.85	62–77	Present study
Laboratory columns	3.0	0.05–1.6	63–85	Hsieh et al. (2007)
Louisburg, N.C.	0.29	0.18	69	Sharkey (2006)
Pilot boxes	0.28–0.88	0.06–0.15	52–99	Davis (2007)
Charlotte, N.C.	0.19	0.13	32	Hunt et al. (2008)
College, Park	0.61	0.15	79	Davis (2007)

Table 6 shows TN removal efficiency from the present study and comparison with previous studies and guidelines (Hsieh and Davis, 2005; UNHSC, 2006; Davis, 2007; Hunt et al., 2006, 2008; Carpenter and Hallam, 2010). They reported wide ranges (30~99%) of TN removal efficiencies, whereas present study found 59–72% TN removal efficiencies. Table 7 shows TP removal efficiencies obtained from different studies and guidelines (Davis, 2007; Hsieh et al., 2007; Hunt et al., 2008; Sharkey, 2006) and comparison with the present study. Again, wide range (32~99%) of TP removal efficiencies were reported; whereas present study found 62~77% TP removal efficiencies. In some cases, the pollutants removal performances for phosphorus were not significant. This may be attributed to the fact that some bound pollutants (especially phosphorus) were mainly associated with smaller particles and trapping of such smaller particles was not achievable through tested filter media. However, for a longer period of such sediment accumulation, the filter media was expected to become clogged and eventually would be able to trap smaller particles (Hatt et al., 2005). However, previous researchers also investigated the TP removal efficiency from different filter media.

From the above-mentioned results, it was found that the tested RAP and CB materials can be used as filter media in bioretention systems and was able to provide expected water quality treatment standards. In reality, 100% pollutants removal efficiency is achievable in many cases, however with the compromise of reducing hydraulic conductivity, which is not recommended with the consideration of urban flooding. As such, there should be always a balance of target pollutants removal efficiency and acceptable hydraulic conductivity. The pollutant removal efficiency can also be increased using larger depth and/or area of filter media, which causes increase in cost. As such a proper cost optimisation is necessary for the decision-making of optimum size of bioretention system. Imteaz and Ahsan (2014) presented detailed cost optimisation of three different systems including bioretention using MUSIC. Also, in many cases 100% removal of nutrients is not necessary or over-optimistic. Australian best management practice guideline recommends achieving captures of 80% TSS, 45% TN and 45% TP (Melbourne Water, 2005).

3.4 Bioretention filter media depth

Filter media is one of the major components of bioretention systems in urban stormwater management. Appropriate filter media depth is required for successful removal of TSS, TN and TP. Table 8 shows effects of filter media depth in achieving 100% pollutants removal efficiencies. Diblasi et al. (2009) suggested that a minimum 300 mm bioretention media depth was required to remove 100% TSS from stormwater. However, in this study the authors suggest that minimum 200–300 mm filter media depth is required to remove 100% TSS from stormwater for these particular C&D materials. Several researchers had found that 100% TP can be removed from stormwater runoff using appropriate filter media depths between 600 mm to 900 mm (Hsieh et al., 2007; Passeport et al., 2009; Hatt et al., 2009). This research suggests filter media depth of 300–1,100 mm is required depending on the materials used to remove 100% TN.

Table 8 Required filter media depths for specific nutrients removal in bioretention systems

Gross pollutants	*Previous studies*		*Present study*
	Study cases	*Typical depth (mm)*	*Recommended depth (mm)*
Total suspended solids	Diblasi et al. (2009)	300	200–300
Total phosphorus	Hsieh et al. (2007), Passeport et al. (2009) and Hatt et al. (2009)	600–900	300–1,100
Total nitrogen	Passeport et al. (2009)	900	300–900

The comparison showed that the minimum required depth for C&D materials was also quite similar with previous guidelines. TN removal efficiency from stormwater runoff had been investigated by Passeport et al. (2009). Based on their research it was concluded that minimum media depth of 900 mm was required for natural soils to remove 100% TN. Current study also suggests that minimum filter media depth of 300–900 mm (depending on the filter material) is essential for RAP and CB as filter media to reduce 100% TN through bioretention systems.

4 Conclusions

Physical and hydraulic properties of the RAP and CB materials were assessed in this research to investigate the suitability of these materials as filter media in bioretention systems. Comparisons were also made between laboratory results and previous guidelines to investigate whether it can satisfy or not with various regulatory authorities' requirements for urban stormwater management systems. Thorough comparison and analysis were performed in this study, which indicated that the selected RAP and CB materials satisfied the criteria for use as filter materials in bioretention systems.

The pH values of the materials indicated the materials to be slightly alkaline, though still within expected limits. The compaction characteristics of the tested RAP and CB materials were found to be in a consistent range and equivalent to those expected of a quarried material. The specific gravity values of the RAP and CB materials were found to meet specified requirements and these indicated that they can be considered high quality aggregates. The organic contents of the recycled C&D materials were found to be low, except for RAP for which the organic content was also found in the acceptable ranges. The flakiness index of CB was observed to be lower than that of RAP. The hydraulic conductivity of the recycled materials can be described as low for CB and high for RAP aggregate.

Among the tested C&D materials, the lower pollutant removal and the higher hydraulic conductivity were obtained from RAP. It was also noted that the permeability values achieved from C&D materials used in this research were within the acceptable limits as filter materials in filter media applications. In general the hydraulic conductivity values of CB and RAP were higher than that of natural aggregate. The hydraulic conductivity values were found to be within the range of those specified for the usage of aggregates as biofilter media in urban stormwater management systems. The permeability values obtained from RAP and CB materials ranged between 44 mm/hand121 mm/h, whereas the minimum requirement was 12.7 mm/h.

For 100% removal of pollutants, bioretention filter media depth was a salient feature. Through MUSIC's simulations required filter media depth was calculated for 100% removal of pollutants. It was found that filter media depth between 300 mm to 1100 mm was required for complete removal of pollutants using selected C&D materials as bioretention filter media. This finding was quite similar to the findings by other researchers and/or available guidelines.

This research highlights the fact that C&D (RAP and CB) materials traditionally destined for landfill can be used in a sustainable manner as an alternative materials in filter media for bioretention systems. The presented results would provide the readers with an indication of the testing methodology, physical properties, chemical properties and performance of these traditionally waste materials in bioretention applications. In terms of entire life cycle of filter materials it is necessary to make sure that groundwater should not be contaminated when C&D materials are reused. Based on the extensive suite of geotechnical and chemical tests, it can be concluded that the RAP and CB materials used in this research are suitable alternative materials for bioretention filter media in stormwater management systems.

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