Stormwater solids removal characteristics of catch basin insert using some geotextiles

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Abstract

Suspended solids in urban runoff have multiple negative hydrological and ecological impacts and create a wide range of water quality problems in receiving water bodies. Geotextile filtration systems inserted within catch basins have the potential to mitigate these effects, through flow attenuation and pollutant removal. This study modelled a catch basin in a column and assessed the hydraulic and solids removal characteristics of three types of non-woven polypropylene geotextiles (NWG1, NWG2, NWG3) to capture solids from stormwater runoff. Synthetic stormwater of TSS concentration 200mg/L was used with two particle size distributions of 0-180µm (P1) and 0-300µm (P2) respectively. The results revealed that the desired stormwater TSS concentration (<30 mg/L; ANZECC, 2000) could be achieved with a short ripening process (e.g., 1-2 kg/m^2 of suspended solids loading) for trials using the larger particle size distribution (P2). In addition, 36% more suspended solids were captured in trials using the soil with the larger range of particle sizes (P2) than for the soil with smaller particle sizes (P1). Geotextile fibre pattern appeared to have a significant influence on the TSS removal capacity. The NWG1 has higher permittivity than NWG3 but similar to NWG2. NWG1 could capture overall more TSS (which also resulted in earlier clogging) than NWG2 and NWG3 because of the special fibre structure of NWG1. The experimental data shows that these geotextiles may start to clog when the hydraulic conductivity reaches below 1.36x10^{-05} m/s. The overall hydraulic performances of geotextiles showed that the NWG1 has better potential for use in CBIs because of its higher strength and multiple reuse capability.

Keywords: Stormwater, Suspended solids; Geotextiles, Catch basin insert, Water quality,

1. Introduction

Urban runoff caused by increasing areas of impervious surfaces such as roads, parking lots, and building rooftops is a major contributor to pollution of water bodies and is a major concern in Australia and globally. Particulate matter including suspended solid (SS) and other pollutants from impervious surfaces are transferred to aquatic biota, and have a wide variety of detrimental effects in aquatic systems (Alam et al. 2017; Zhao and Li 2013). Different best management practices (BMPs) have been introduced for sediment control which include gross pollutant traps, constructed wetlands, retention ponds, detention basins, grass swales, vegetated filter strips, biofilters, sand filters and catch basin inserts (CBIs) (Alam et al. 2017; Hatt et al. 2009). Land development and construction sites are major contributors to total suspended solids (TSS) in stormwater which can be reduced up to 85-90% by using proper erosion control devices (Taylor and Wong, 2002; Schueler and Holland, 2000; Lehner et al., 1999). Well-planned, designed, executed and upheld sediment controls can remove stormwater TSS by up to 60 - 70% (DoW, 2009; Schueler and Holland, 2000). Most of these technologies can effectively reduce stormwater TSS concentration but require significant land area and incur costs to maintain filter media after clogging.

Among all of the above technologies, CBI is a promising tool for solids removal from stormwater runoff at the source. CBIs are typically mounted within catch basins (e.g. side entry pits) that do not require any extra land and are easy to clean, replace and reuse (Alam et al., 2017). A few studies have focused on TSS removal using CBIs in side entry pits prior to entry into the drainage system (ICBIC 1995; Lau et al. 2001; CIWMB 2005; GeoSyntec and UCLA 2005; Kostarelos and Khan 2007). The ICBIC (1995) tested five different CBIs under field conditions and found TSS removal efficiency up to 73%. Edwards et al. (2004) evaluated four different inserts by using a pilot scale catch basin and synthetic stormwater and found removal efficiency at 10-19%. Lau et al. (2001) performed a series of tests using CBI under field conditions and found the TSS removal efficiency to be 78-99% for particles of 100-400 µm. Morgan et al. (2005) reported a TSS removal efficiency of 11-42% for a series of controlled tests using CBI. TSS removal efficiency of six CBIs was observed by Kostarelos and Khan (2007). They studied the removal of TSS at three different flow rates (50, 150 and 300 L/min) with three contaminant concentrations (low, medium, high) and found the efficiency to be up to 96% and 50% for lab and field conditions, respectively. Although different types of CBIs are now available, there is a dearth of information on the science behind the hydraulic and TSS removal characteristics for capturing solids from stormwater using geotextiles as filter material.

Geotextile, a permeable geo-synthetic, is a potential candidate to filter and separate debris and impurities from water which has been widely applied in geotechnical and environmental fields (Leverenz et al. 2000, Nagahara et al. 2004, Bouazza et al. 2006, Muthukumaran and lla mparuthi, 2006, Vaitkus et al. 2007, Lamy et al. 2013). Geotextile fabric commonly comprises woven or nonwoven polypropylene or polyester. Woven fabric is designed for separation and reinforcement applications (Bouazza et al. 2006). Nonwoven (needle punched) geotextile is designed for filtration (Leverenz et al. 2000, Lamy et al. 2013), separation (Vaitkus et al. 2007), liner protection (Nagahara et al. 2004) and drainage applications (Muthukumaran and llamparuthi, 2006). It has been reported that geotextile based filters may clog for particle sizes 7-50 µm due to mechanical filtration (Faure et al. 2006). Franks et al. (2012) reported on criteria for retention of sand particles on geotextiles for two particle size distributions (PSD1: 0-106 µm and PSD2: 0-180 µm) in stormwater runoff, observing that a geotextile filter with an apparent opening size (AOS) of 150 µm is effective in reducing the TSS concentration. Palmeira et al. (2008) observed the biological clogging of geotextile for long term permittivity testing and Mulligan et al. (2009) used laboratory tests to determine the efficiency of non-woven geotextile to remove contaminated suspended solids from surface water. Reviews of the interaction of geotextile with contaminated aqueous phase include Sangam and Rowe (2001), Athanasiadis et al. (2004), Rowe et al. (2005), Kalinovich et al. (2008) and Boutron et al. (2009).

A new type of CBI has been recently introduced by Urban Stormwater Technologies Pty Ltd (UST) to remove stormwater pollutants at source in the drainage systems of city councils in Western Australia (Rothleitner, 2011). Recently, Alam et al. (2017) carried out a field survey to characterize the gross pollutants captured in the geotextile used in CBI of UST and found it effective specially for vegetation (>90% captured). The UST CBI uses a special type of non-woven geotextile. To date, no data on this UST geotextile has been reported in the literature for the removal of TSS from stormwater in CBI applications. The objective of this research was to investigate the hydraulics of solids removal characteristics from stormwater in CBIs using different non-woven geotextiles, including the UST geotextile and two other commercially available types.

2. Materials and methods

2.1 Geotextiles selection

Three types of commercial geotextiles (NWG1, NWG2, NWG3) were selected for this study. The NWG1 was obtained from UST while other two (NWG2 and NWG2) are readily available in the market. The selection criteria of these geotextiles were based on their apparent opening sizes (AOS), thickness and G-rating. These parameters are further explained in SI (Supplementary information). However, currently the G-rating of NWG1 is not available. The NWG1 is a special type of geotextile which has unique fibre arrangement compared to NWG2 and NWG3. The speciality in the structure of NWG1 is that it is made of multiple pieces of fabric used in composite to make it stronger and more durable, allowing it to keep its original shape for heavy load and multiple reuses. The soil particles in stormwater are only captured on the external layer of geotextile. Thus, the captured particles can easily be removed or cleaned by reverse flushing with high water flow (400-450 kPa) and reused more than 10 times keeping its original shape intact (Alam et al. 2017). Due to its reusable properties, the disposal load of this non-biodegradable polypropylene (NWG1) material will be reduced and after the end of its use as a CBI insert, the polymer can be reused as raw material for other products. The NWG2 was chosen because of its similar thickness and permittivity to NWG1. The NWG3 was chosen based on its G-rating, thickness and the fibre arrangement similar to NWG2. The physical and hydraulic properties of each geotextile are given in Table 1.

Table 1 Physical and hydraulic properties of geotextiles used in this study

		Hydraulic properties				Mechanical properties		
Name	Structure and materials	Flow rate, Q (L/min/m^2) Mean	Permit tivity ψ (s^{-1})	Hydraulic conductivity, K (m/sec)*10^{-4}	Apparent opening size (AOS)-O_{95} (mm)	Unit wt. (g/m^2)	Thick ness, T(mm)	G-Rating
NWG1	NP, STF, PP	3080	0.68	23.85	0.10	525	3.5	n.a.
NWG2	NP, STF, PP	4800	0.8	24.8	0.075	450	3	6000
NWG3	NP, STF, PP	2100	0.35	14.7	0.06	1200	4	11700

NWG: nonwoven geotextiles, NP: needle-punched, STF: staple fibre, CF: continuous filament, PP: polypropylene, all properties are AS 3706 & Austroads standards and manufacturer's minimum average roll value (MARV) for each geotextile, Tensile strengths are machine direction values, permittivity is equal to hydraulic conductivity normalized by thickness. n.a.: Not available

2.2 Soil samples and stormwater preparation

Washed chemical free sandy and silty soils were collected from Cook Industrial Minerals (CIM, Perth Western Australia) and used to prepare suspended solids with particle size distributions (PSD) similar to the solids found in urban stormwater runoff (Alam et al. 2017; Siriwardene et al. 2007; Wong et al., 2006). The suspended solids samples were prepared by the sieve analysis method AS 1289.3.6.1 (Standard Australia, 2009) with ISO 3310: BS 410-1:2000 sieve sizes 20, 63, 75, 106, 150, 180 and 300 µm. Hydrometer tests were conducted according to AS 1289.3.6.3 (Standard Australia, 2009) to determine the PSD of fine grained soil passing through the BS standard sieve size 75 µm. Synthetic stormwater was prepared with two soil types, P1 and P2. Soil type P1 was prepared by combining graded soil samples to obtain a PSD of 0-180 µm with a D_{50} of 106 µm (P1), while P2 contained particle sizes measuring 0-300 µm with a D_{50} of 150 µm. The uniformity coefficient (C_U) and coefficient of concavity of P1 and P2 were calculated as 27, 0.25 and 4.25, 2 respectively. Synthetic stormwater of TSS concentrations (200 mg/L) was prepared by mixing the soil samples, P1 and P2 (6 g each) with tap water (30 L) at ambient temperature. The further explanation of selection criteria has included in SI.

2.3 Experimental set up

A plexiglass laboratory column of 130 mm diameter and 350 mm length was constructed to model the CBI for capturing solids from storm drainage systems (Fig 1). Other materials used for the column experiments included a pump, a stirrer, a 30-litre plastic tub to hold the synthetic stormwater, tubing to carry synthetic runoff into the column, 500-mL plastic sampling containers, the geotextile filters and a diffuser for energy dissipation while pumping stormwater into the column.

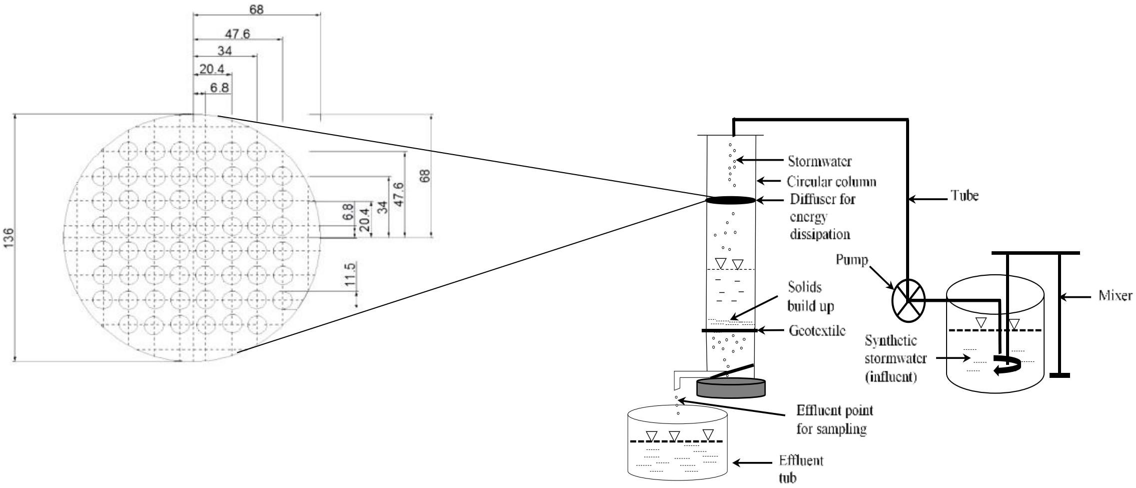


Fig. 1. Schematic diagram of experimental set up (all dimensions in mm)

2.4 Experimental method

The synthetic stormwater solution was pumped into the column inlet in a manner that would best simulate drainage into the CBI during a storm event. A mechanical stirrer agitated the stormwater solution at 100 RPM to maintain particles as a suspension. Uniformity of the TSS concentration in the inlet tank was ensured by monitoring of subsamples taken periodically at different tank depths during each experiment. The stormwater flow rate into the column was 6 mL/sec and the hydraulic loading rate (HLR) was 0.45 mm/sec (64 in/hr). This flow rate was chosen assuming a runoff area to drainage area ratio of 50 (Franks et al. 2012) and rainfall intensity of 3.4 cm/hr, which is 10 times greater (considering the worst condition in the field) than rainfall intensity found for 20 years average recurrence interval (ARI) for 1 hour rainfall intensity in Perth Western Australia (BoM, 2015). Subsamples of influent and effluent were collected every 10 minutes and TSS concentrations were measured using Standard Method 2540B (Eaton et al. 1995). The effluent flow rate was measured to check the reduction of infiltration due to sediment accumulation. The head loss due to sediment deposition was measured as the level in the column rose. The hydraulic conductivity was calculated assuming the total head loss occurred above the full depth of soil fabric system. A total of 4-6 data points were obtained in each test; the average value of the points that were within a relative standard deviation of 25% or less were used. Hydraulic conductivities were calculated for each geotextile using the same method. Each test duration was 80 minutes. Ten influent and effluent samples were collected during each event and TSS concentrations for all samples were used to determine the event mean concentration (EMC) using the following equation (Chow et al. 2011; Meng Nan et al. 2011; Lee and Bang 2000):

$$EMC = \frac{\sum_{i=1}^{N} C_i Q_i \Delta t_i}{\sum_{i=1}^{N} Q_i \Delta t_i} \quad (1)$$

where, C_i is the TSS concentration of each sample within an event I, Q_i is runoff flow rate of the sample calculated by measuring the volume of water exiting the column in a given amount of time; and Δt_i is the time interval between the samples (Taebi and Droste 2004).

The filter system was air dried for 1-2 days in between consecutive runs. A total of 15- 92 experimental runs were carried out for different geotextile types depending on particle size distributions until clogging occurred. The filter system was assumed to be clogged whenever the water level in the column reached the top of the column within 20 minutes of testing or until the filter was clogged, similar to the methodology of Franks et al. (2012) who assumed a linear increase in head loss in a typical underground sand column system. An increase of water level in a typical vertical clearance (1 m) of an underground sand column system within the average duration of a rainfall event (1 hr) is equivalent to reaching the water level in the column at the top (30 cm) in 20 minutes of testing. Duplicates of each test were carried out and if the standard error was more than 5%, the test was repeated.

Stereomicroscopic images were obtained for both virgin and used geotextiles (NWG1, NWG2 and NWG3) by cutting 3 to 5 specimens to obtain three cross sections and one to two planar sections. The geotextile specimens (25 x 25 mm) were air dried at room temperature (20°C) for 24 hrs and placed on a square flat surface to ensure that a cleaned and smooth surface was obtained for image analysis under a low magnification light stereomicroscope (Aydilek et al. 2002); Nikon SMZ800 stereomicroscope with a Schott KL1500 LCD light source, a Toupcam UCMOS14000KPA camera and ToupView 3.7 software; microscope lens Plan 1X, zoom range 1x to 6.3x.

3. Results and Discussions

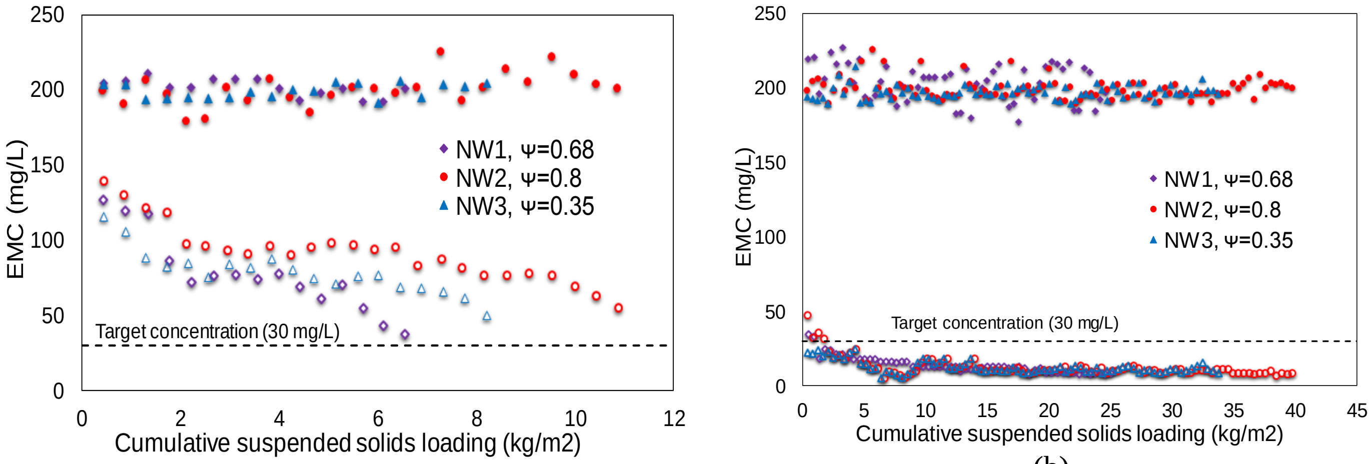
3.1 TSS Removal

Tests for TSS removal were performed to check the optimum capacity of the geotextile fabrics to capture suspended solids while allowing water to pass through freely. The influent and effluent TSS concentrations were measured at 10 minute intervals: effluent concentrations were found to decrease with increasing influent solids loading. EMCs of influent and effluent were calculated as a function of cumulative mass loaded to each geotextile for both particle sizes (Fig 2). EMC values were calculated for each test (80 minutes) until clogging occurred. For P1, for all three geotextiles, the targeted effluent concentration of 30 mg/L (ANZECC, 2000) could not be attained prior to clogging occurring (Fig 2a), although it was attained for P2 (Fig 2b). It should be noted, however, that the ANZECC guideline is for point source pollutant discharge, rather than stormwater pollution which is a non-point source discharge.

TSS accumulation on geotextiles is said to follow the filter ripening process, as the effluent concentration decreases gradually, while the removal efficiency of the filter increases (Clark et al. 1992). The ripening process may be explained as the particles built up in and on the filter to enhance the filter retention capacity (Mao et al. 2006). Ripening has a drastic effect on the removal efficiency of a filter because of the subsequent effect of the captured particles on solids accumulation. The ripening process for NWG1, NWG2 and NWG3 occurred at a total suspended solid loading of 1.35, 1.72 and 0.88 kg/m^2 respectively. The ripening process of NWG3 occurred earlier because of its smaller apparent opening sizes.

Due to the difference in fibre structure, more of the smaller particulate material was removed and consequently, effluent TSS concentrations in NWG1 decreased rapidly in the latter stage of the test, with clogging of the filter occuring faster than for the other two (total loading 6.56 kg/m^2). Effluent TSS in NWG2 was higher due to its larger AOS and permittivity, as also noted by Kutay and Aydilek, (2004). Their study revealed that the percentage of solids passing through the geotextiles increases with increasing AOS and permittivity (the hydraulic conductivity normalized by the thickness). A similar range of ripening period (1-2 kg/m^2) was observed by Franks et al. (2012) but the corresponding drop in TSS differed slightly from this study because of differences in PSD. For a similar range of soil particles (0-180μm) with D_{50} (106 μm), the Cu (12) value of their soil was almost half that in this study. This shows the importance of soil gradation in applications such as geotextile filtration, i.e. the importance of different grain distribution parameters, in addition to D_{50} (Coduto 2011). Additionally, the properties of geotextile (AOS, permittivity, thickness and hydraulic conductivity) used in this study differed from this previous research (Franks et al. 2012). TSS removal also depends on the AOS of geotextile and the median grain sizes (D_{50}). The D_{50} of P1 (106 μm) indicates that 50% of the particles in this sample were larger than the AOS of geotextiles (Table 1). However, the geotextiles captured more than 50% of stormwater TSS, with the extent of capture increasing due to the ripening process (Fig 2a). The clogging points were obtained when the effluent concentrations of NWG1, NWG2 and NWG3 had decreased to 82%, 75% and 73% of their initial concentrations. Statistical analysis (two-tailed t-test) confirmed (1% significance level) that there was no significant difference ($p>0.01$) for concentration decrease amongst the three geotextiles for P1 and P2 at but significant variation ($p<0.01$) in concentration decrease was found between P1 and P2 for the same type of geotextile. Even though the AOS of NWG1 was the highest, it clogged first because of its special type of fibre structure.

The total solids at the clogging point for P2 was found to be higher than for P1 because of the greater range of particle sizes. Clogging occurred at the lowest total solids loading for NWG1 (6.56 kg/m^2), followed by NWG3 (8.21 kg/m^2) and NWG2 (10.86 kg/m^2) respectively for P1. A similar trend was also observed for P2: NWG1 (25.03 kg/m^2) < NWG3 (33.77 kg/m^2) < NWG2 (39.79 kg/m^2). Higher permittivity is expected to result in a greater mass of solids loaded to the filter before its final clogging point (Kutay and Aydilek, 2004) which was observed for NWG2 and NWG3 but not for NWG1. Although the permittivity of geotextiles varied between 0.35-0.8 (s^{-1}) (Table 1), the fibre structure of NWG2 and NWG3 was completely different than NWG1. The special type of internal fibre structure of NWG1, led to faster clogging than for the other two geotextiles.



(a) (b)

Fig 2. Effect of cumulative mass loaded to each filter for TSS concentration of 200 mg/L for particle size distribution (a) P1 (0-180 µm) and (b) P2 (0-300 µm). Filled symbols indicate influent concentration and open symbols indicate effluent concentration. Initial permittivity values are given in legend for each geotextile.

3.2 Effect of geotextile fibre pattern on filtration

Even though the influent concentration was constant for all tests, the effluent TSS concentration showed significant variation for the different geotextile filter materials. NWG2 had the greatest TSS effluent concentration (EMC) for P1 followed by NWG3 and NWG1 respectively (Fig. 2a). This shows that NWG1 has the capacity to capture the greatest amount of TSS from stormwater runoff prior to clogging. This observation can be partly explained by analysis of the arrangement of fibres within the different geotextiles materials. The NWG1 material was designed to provide specific water filtration qualities using a patent pending process. (reference patent pending number). Stereomicroscopic imaging of planar and cross-sectional views of the geotextiles clearly indicates the differences in fibre arrangement between the geotextiles (Fig 3). The NWG2 and NWG3 images show similar patterns which differ from NWG1.

Although the pore size of NWG1 (150 µm) is larger than for NWG2 and NWG3, the permittivity of NWG1 is similar to that of NWG2 (Table 1). As shown in Fig. 3 (d), the bulk of TSS particles were captured in the top portion of the filter in NWG1 while in NWG2 and NWG3, the particles were distributed throughout the entire thickness of the material. In NWG1, at least half of the filter thickness was relatively free of the particulates whereas in NWG2 and NWG3 the particulates had permeated through the filter material. The images in Figure 3 suggest that particles are more easily able to pass through NWG2 and NWG3 than NWG1, explaining the observation that NWG1 has greater capacity to capture the smaller particles. For NWG1, breakthrough of small particles is less likely and the clogging of NWG1 occurs when the material has captured the maximum amount of small particles; however, for the other two materials, breakthrough occurs preferentially, allowing the small particles to pass through the filter.

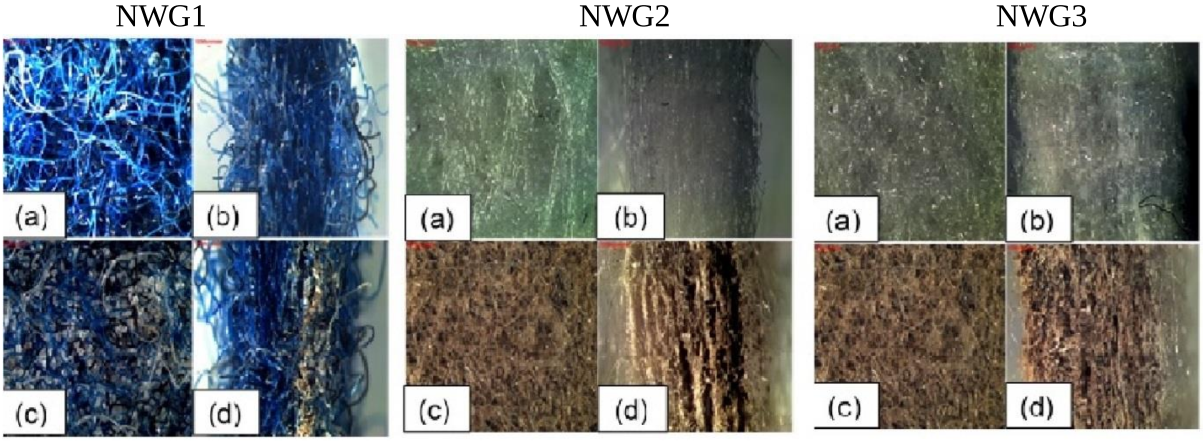


Fig. 3 Stereomicroscopic image of NWG1, NWG2, NWG3 respectively (a) planar and (b) cross-sectional images of the virgin geotextile and (c) planar and (d) cross sectional images of the clogged geotextile.

3.3 Effect of PSD on filtration

For all three geotextile materials tested, the soil type with the larger PSD range was more effectively captured and generally resulted in more efficient filtration. The total solids loaded and captured for both soil types (P1 and P2) were calculated from the EMC of influent and effluent (Table 2). For P1 (0-180 μm), NWG1 and NWG3 showed similar capture capacities of 61%, slightly higher than for NWG2 (54%), which may have been due to differences in hydraulic properties and the apparent opening sizes (AOS) of the geotextiles. In contrast, the cumulative TSS loaded for the sand sample, P2, was significantly larger than for P1 (around 93% solids captured; Table 2). The three geotextiles clogged at an average of 8.54 kg/m^2 suspended solids loaded, with 4.96 kg/m^2 suspended solids captured for P1, while geotextiles with P2 were clogged at an approximately 30.76 kg/m^2 TSS loading with 32.88 kg/m^2 captured. Therefore, on average, 36% more suspended solids were captured in the sample with the larger particle size distribution than for the smaller size particles, indicating that smaller particle sizes led to clogging much more readily than samples containing larger particles. For P1 the geotextiles became clogged after 15-23 experiments, while for P2, 59-92 experiments were needed for the materials to clog, which indicates that the number of rain events required to clog the CBI insert materials would be 4 times higher for soil types of P2 (larger PSD and larger range of PSDs) than for P1 soil types. This is due to the effect of ripening and captured solids in a filter, which depends on the grain size distribution and morphology of the previously captured particles in the media depth of the filter (Clark et al. 1992). Statistical analysis (two-tailed t-test) confirmed (1% level of significance) that there was no significant difference ($p>0.01$) of cumulative TSS captured for P1 among the geotextiles. However, a significant variation ($p<0.01$) was found for NWG1 with respect to NWG2 and NWG3 but no significant difference was found between NWG2 and NWG3 for P2. A significant difference ($p<0.01$) for cumulative TSS captured was found between P1 and P2 for each type of geotextile at 1% level of significance. Capture and accumulation of smaller, more uniform particles creates denser packing which leads to earlier clogging. During the experiments, suspended solids in the stormwater mixture accumulated to form a cake layer on the surface of the geotextile (Clark et al. 1992). This accumulated cake layer formed another filter zone above the geotextile which effected further retention of particles. As the cake layer increased, smaller particles were entrapped in the voids of the existing layer, reducing the overall porosity and void ratio which ultimately resulted in clogging. The sand sample P2 (0-300 µm) had a higher accumulation of sand particles than P1 (0-180 µm), forming a thicker cake layer, demonstrating how the greater range of particle sizes has generally higher porosity with the same mass of solids captured as compared to poorly graded particles. As larger particle sizes (e.g., P2) were captured on the geotextile, the retained suspended solids overlapped on the surface of the geotextile forming a graded filter zone. This zone may be more porous allowing more particles to settle before clogging, and thereby allowing effective filter operation for a higher number of rain events. Similar observations on the impact of particle size distribution on solids capture were reported by Franks et al (2012) (Table 2). These authors used two particle size distributions PSD1 (C_U = 35) and PSD2 (C_U = 12) with median grain sizes of 50 and 106 µm respectively and three non-woven geotextiles with AOS of 180 µm (Geo 1), 150 µm (Geo 2) and 150 µm (Geo 3) respectively. In their study, the larger particle size distribution PSD2 (0-180 µm) was captured, on average, 29% more effectively than the smaller particle size distribution PSD1 (0-106 µm) for the three geotextiles.

Table 2 Summary of total solid loaded and captured

PSD	Geotextile types	Total solids loaded (kg/m^2)	Total solids captured (kg/m^2)	Percentage captured	Ref.
P1 (0-180 µm)	NWG1	6.56	3.98	60.74	This study
	NWG2	10.87	5.86	53.89	
	NWG3	8.21	4.97	60.51	
P2 (0-300 µm)	NWG1	25.03	23.31	93.12	
	NWG2	39.79	37.29	93.72	
	NWG3	33.77	31.62	93.63	
PSD1 (0-106 µm)	Geo 1	3.75	0.25	6.67	Franks et al. (2012)
	Geo 2	4.33	3.57	82.45	
	Geo 3	3.41	2.57	75.37	
PSD2 (0-180 µm)	Geo 1	10.80	8.10	75.00	
	Geo 2	6.37	5.57	87.44	
	Geo 3	4.17	3.76	90.17	

The effect of PSD on the solids capturing capacity can be further explained by the use of classic steady state filtration theory (Tufenkji & Elimelech 2004):

$$\frac{Ce}{C_0} = \exp\left(-\frac{3}{2}\frac{(1-n)}{d_c}\alpha\eta T\right) \qquad (2)$$

where C_0 and Ce are influent and effluent TSS concentrations, n is the filter bed porosity, α is the striking coefficient (determined from column test, Li and Davis, 2008), η is the single collector contact efficiency, d_c the diameter of spherical collector (media particle) and T is the media depth (e.g., geotextile thickness). This equation indicates a sharp exponential decrease of particle concentration throughout the media depth, i.e., the increase in media depth will decrease the effluent concentration (AWWA, 1999). However, this equation is used in the context of a clean bed and therefore does not account for the accumulation of solids deposited in the filter. In addition, in this study, the outlet flow rate was not constant due to solids accumulation and therefore the conditions were not in a steady state. Therefore, the assumption of steady state was made using granular bed filtration theory, as was also done in the study by Frank et al (2012). In the first set of experiments, the geotextile may be considered as a clean bed and this equation was used for the results obtained from the first test. To make the equation simple, the variables α, η and d_c in equation (2) are transformed into a single constant, Z:

$$\frac{C}{C_0} = \exp\left(-\frac{3}{2}Z(1-n)T\right) \qquad (3)$$

The Z values obtained from six tests (for geotextile as clean bed) using Eq (3) are listed in Table 3. The results of the Z value increase with decreasing permittivity and increasing unit weight (Table 1 and 3). Again, if it is assumed that α, the striking coefficient and η, the single collector collision/contact efficiency remain constant for all three geotextiles for one particle size distribution, an increase in Z indicates a decrease in d_c (diameter of the spherical collector). Therefore, it can be explained that the unit weight and diameter of a spherical collector behaves similar to permittivity. These results indicate that decreasing the diameter of the spherical collector also decreases the pore spaces between the particles and as a result, the filter media become less permeable. Similar explanations can be drawn for unit weight. Values in Table 3 indicate larger Z values for P2 particle size distribution than for P1. Further if it is assumed that α and d_c remain constant for the same geotextile then η, the single collector collision efficiency depends on particle size distribution. This phenomenon follows the granular filtration theory that larger particles have an affinity to collide more with a collector via sedimentation and interception mechanism. These results are similar to those of Li and Davis (2008).

Table 3 Trend analysis of Z for the reduction of initial concentration for six tests

PSD	P1			P2		
	NWG1	NWG2	NWG3	NWG1	NWG2	NWG3
C_o	205	199	204	219	198	193
C	126	139	116	34	47	22
Z	457	396	472	1765	1596	1793

3.4 Hydraulic conductivity

Hydraulic conductivity was taken as the average of 4-5 readings for each 80 minute test (equivalent to one rain event). Hydraulic conductivities for each test event (15-92 test events) as a function of cumulative suspended solids captured for P1 and P2 are shown in Fig. 4. The results revealed that more cumulative mass was captured with P2 (0-300 µm) than P1 (0-180 µm) for the same hydraulic conductivity. For instance, NWG2 captured 3.5 times more P2 sand samples than P1 for the same hydraulic conductivity of $1.3\text{x}10^{-05}$ m/s. Similarly, NWG1 and NWG3 captured 6.3 and 7.3 times more P2 than P1 with hydraulic conductivities of $1.9\text{x}10^{-05}$ m/s and $1.2\text{x}10^{-05}$ m/s respectively. These results show that for the soil with larger particle sizes more was captured at the same hydraulic conductivity than for soil with smaller particle sizes. This means the particle size distribution greatly influenced the hydraulic conductivity of geotextile filtration system.

In addition to the effect of PSD on hydraulic conductivity, there were also differences due to other factors such as geotextile type. As shown in Fig. 4, the hydraulic conductivities for all three geotextiles at the clogging point varied between $8.50\text{x}10^{-06}$ m/s to $1.36\text{x}10^{-05}$ m/s. NWG2 had the highest average hydraulic conductivity followed by NWG1 and NWG3 respectively. Similar hydraulic conductivities for nonwoven geotextiles at the clogging point were also found by Frank et al., (2012). Therefore, in general, the geotextiles would start to clog when the hydraulic conductivity reached below 1.36x10^{-05} m/s. However, the variation of hydraulic conductivity at the clogging point depends on the type of geotextile and soil sample gradation.

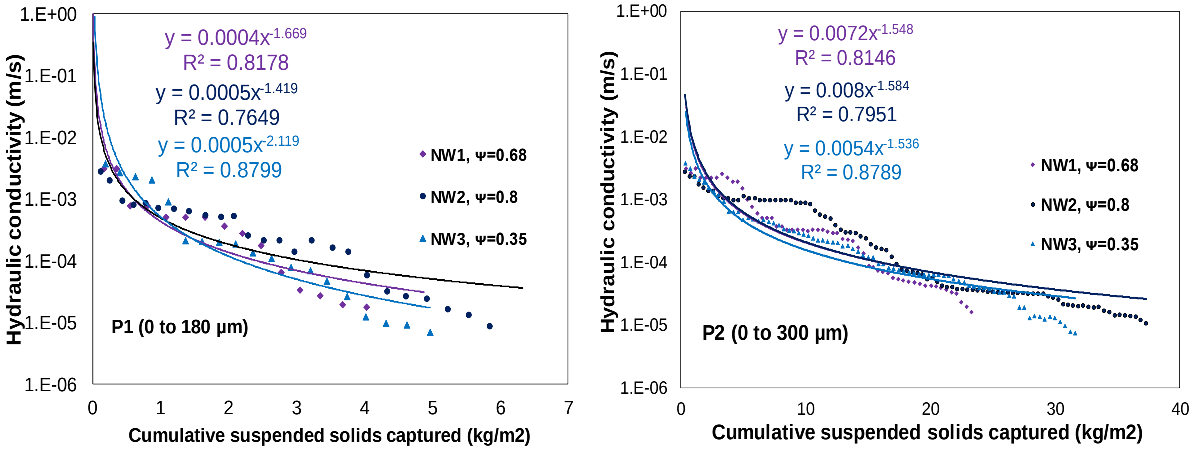


Fig. 4 Hydraulic conductivity of each filter as a function of cumulative suspended solids captured

The hydraulic conductivities found in this study are similar to those of mixed media filters (such as sand filters and geotextiles) and hence they can be compared with other media-based stormwater filtration systems (Clark and Pitt, 2009). Urbonas (1999) developed an equation describing the performance of different natural filters which shows that the unit flow velocity through a natural media is directly related to the amount of sediment loaded onto the filter surface. Clark and Pit (2009) later applied and validated this equation for mixed media filtration systems. Franks et al. (2012) used this equation directly for geosynthetic filtration for cumulative captured solids onto geotextiles and the suggested power equation of Urbanas (1999) for predicting the unit flow velocity (u) is:

$$u = X\left(\frac{M_m}{A}\right)^{-y} \tag{4}$$

where X and y are the best fitted parameters for empirical flow through and exponential constant, M_m is the loaded (L_m) or captured solid (C_m) mass onto geotextile filter and A is the loaded or captured cross sectional area of the geotextile. It was assumed that the filtration process for a soil fabric filtration system is similar to that for mixed-media filters: the different parameters of Eq (4) were calculated and compared for this study and for those of Clark and Pitt (2009) who used a mixed media filter of fine sand, peat moss, activated carbon and compost, and Franks et al. (2012) (Table 4). Clark and Pitt (2009) used the constant head method to determine hydraulic conductivity while this study used the falling head method similar to Frank et al (2012). As indicated in Table 4, the values of X in Frank et al. (2012) and Clark and Pitt (2009) vary between 2.77x10^2 to 2 x10^9 and 1.55x10^3 to 6.3x10^{13} respectively and the values of y vary between 0.594-2.96 and 0.227-4.09 respectively. The values of X and y found in this study are within the range of this previous research. However, Frank et al (2012) found that the X and y values for their geotextiles decreased with the increasing AOS and permittivity. The results in this study also showed that the X and y values for all geotextiles decreased with increasing AOS and permittivity for P1 (0 to 180 μm). However, this trend was not evident for P2 (0 to 300 μm) presumably due to its larger particle size distribution. This observation shows that AOS and permittivity cannot be used as the sole parameters for modelling of hydraulic conductivity as a function of solids loading and that particle size distribution must also be considered when modelling TSS removal from stormwater using geotextiles.

Table 4 The empirical flow through and exponential constant parameters for geotextile and sand filtration system

Ref.	Filtration media	Conc. (mg/L)	Clogging K (m/s)	Model parameters			Model equation
				X	y	R^2	
This study	NWG1-P1	200	9.73×10^{-06}	3.82×10^{6}	1.67	0.818	$u = X(\frac{C_m}{A})^{-y}$
	NWG2-P1		1.03×10^{-05}	7.78×10^{6}	1.42	0.765	
	NWG3-P1		8.90×10^{-06}	1.02×10^{8}	2.12	0.880	
	NWG1-P2		1.44×10^{-05}	2.73×10^{7}	1.55	0.814	
	NWG2-P2		8.35×10^{-06}	5.46×10^{7}	1.58	0.795	
	NWG3-P2		1.36×10^{-05}	1.89×10^{7}	1.54	0.878	
Franks et al. (2012)	Geo 1- PSD1	200	3.76×10^{-04}	N/A	N/A	N/A	$u = X(\frac{Cm}{A})^{-y}$
	Geo 2-PSD1		4.85×10^{-06}	5.11×10^{5}	1.76	0.886	
	Geo 3- PSD1		3.48×10^{-06}	2.00×10^{9}	2.96	0.959	
	Geo 1- PSD2		1.64×10^{-05}	2.77×10^{2}	0.59	0.653	
	Geo 2-PSD2		4.16×10^{-06}	1.02×10^{4}	1.22	0.868	
	Geo 3- PSD2		3.05×10^{-06}	4.17×10^{5}	1.75	0.904	
Clark and Pit (2009)	Sand	400	n.a.	4.45×10^{4}	1.02	0.734	$u = X(\frac{L_m}{A})^{-y}$
	Carbon sand			1.40×10^{4}	0.77	0.611	
	Peat sand			2.00×10^{3}	0.71	0.818	
	Compost sand			1.60×10^{13}	4.09	0.998	
	Sand	150	n.a.	1.55×10^{3}	0.22	0.882	
	Carbon sand			6.30×10^{13}	5.17	0.541	
	Peat sand			5.10×10^{3}	0.40	0.581	
	Compost sand			1.6E+13	4.09	0.997	

**L_m/A and C_m/A are* cumulative loaded and captured mass of solids on/in filters (g/m^2) respectively. Units of *K* is m/day

Geotextiles used in this study showed significant potential for TSS removal from stormwater but the selection of geotextile type for CBI needs careful consideration including physical and hydraulic properties. With an influent concentration of 200 mg/L and a runoff coefficient of 0.9 (Alam at al. 2017), the NWG1, NWG2 and NWG3 were found to clog at 0.72- 1.2 m (P1) and 2.77-4.42 m (P2) of total rainfall. Considering the average yearly rainfall of Western Australia 1 m (BoM, 2015), the NWG1, NWG2 and NWG3 would require maintenance of 262, 422 and 332 days respectively for P1. The maintenance time of NWG1 was found to be less than this because it becomes clogged more rapidly. Under current operation, NWG1 in CBI is currently serviced (e.g. maintained) 10 times a year (Alam et al., 2017). The servicing frequency of CBI is an important parameter that depends on other factors such as runoff characteristics, location, season and traffic volume. When the geotextiles are used in water with high organic content (especially road runoff and runoff from parking lots), biological growth may also occur in and on the geotextile (Palmeira et al. 2008; Korkut et al. 2006). This biological activity may limit the hydraulic conductivity of geotextile enhancing early clogging. However, further research is needed to determine the servicing frequency of geotextile CBIs for their optimum efficiency. Additionally, the non-woven geotextiles are currently non-biodegradable polypropylene materials which may have adverse environmental effects and hence it is necessary to develop a biodegradable geo-fabric material for use as CBI to clean stormwater at the source.

3.5 Conclusion

This study evaluated the hydraulic performances of three geotextiles for capturing two types of stormwater TSS in CBI. The filtration performances of the geotextiles were found to be dependent on the geotextile physical properties and the PSD of the suspended solids. It was found that the effluent TSS concentration target value of 30 mg/L (ANZECC 2000) could be attained for the soil type with the larger PSD (P2; 0-300 µm) after a short filter ripening period. The ripening period for both particle size distributions occurred between 0.8-1.88 kg/m^2 of cumulative suspended solids loading. The cumulative solids loading onto geotextiles varied between 6.56-39.79 kg/m^2 depending on particle size distribution and the results indicate that 36% more of the larger particle size distribution (P2) was captured than the smaller particle sizes (P1: 0-180 µm). In general, the coarser particle size distribution (P2) resulted in a greater percentage of solids captured (93%) than a finer particle size distribution (P1) because of clogging at a lower percentage of solids captured (53-60%). The hydraulic conductivity values were also consistently larger for the experiments with larger particle size distribution (P2), because of the expected formation of a more permeable graded filter zone. The clogging point is an important hydraulic parameter for geotextile filtration and it occurs between the hydraulic conductivity of 8.50×10^{-06} m/s to 1.36×10^{-05} m/s. Based on the results, it was revealed that the NWG1 may be suitable for stormwater CBI because of its unique structure and capacity for reuse over the other two materials tested. This study considered only three geotextiles and two particle size distributions and further research is needed to select appropriate geotextile types from a wide range of geo-fabrics and soil types for optimum efficiency in CBIs to clean stormwater at source.

Notation	**unit**
A: loaded/captured area of geotextile	m^2
C_i: Influent EMC	mg/L
Ce: Influent EMC	mg/L
C_U: coefficient of uniformity	dimensionless
Cc: coefficient of curvature	dimensionless
C_m: cumulative captured solid mass onto geotextile at the time clogging	gm
D: particle sizes	µm
D_{50}: the grain diameter at 50% passing respectively	µm
d_c: the diameter of the spherical collector	dimensionless
K: hydraulic conductivity	m/sec
L_m: cumulative loaded solid mass onto geotextile at the time clogging	gm
M_m: cumulative loaded or captured mass of solid onto geotextile	gm
n: the filter bed porosity	dimensionless
O_{95}: apparent opening size	µm
O: geotextile pore sizes	µm
Q: unit flow rate	L/min/m^2
Q_i: unit flow rate in a given amount of time	L/min/m^2
T: thickness of filter	mm
u: unit flow velocity	m/day
X: flow through constant	dimensionless
y: exponential constant	dimensionless
Z: transformed constant	dimensionless
Δt_i: the time interval between the samples	s
Ψ: permittivity	s-1

α: The striking coefficient	dimensionless
η: the single collector contact efficiency	dimensionless

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