Effectiveness of Compost Biofilters in Removal of Sediments from Construction Site Runoff

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The effectiveness of compost biofilters in removal of suspended sediments from stormwater runoff was evaluated. Field experiments were conducted in the summer of 2006 at the Guelph Turf Grass Institute, University of Guelph, to verify the sediment removal efficiency of the compost biofilter from synthetic stormwater runoff. The average sediment removal efficiency of 8-inch (20-cm) compost biofilters (socks) for 5, 10, and 15 rolls were 34, 48, and 60%, respectively. The average sediment removal efficiency for 18-inch (45-cm) socks for 5, 10, and 15 rolls were 69, 84, and 95%, respectively. The decrease in sediment removal efficiency of the biofilter over time was significant. The average sediment removal efficiency of 5 rolls of the 18-inch (45-cm) sock started to decrease gradually from 70 to 62, 58, 56, and 54% after 1, 5, 10, 15, and 20 consecutive runs. Sediment removal efficiency of the biofilter for sediment particles in the size range of clay was found to be 30%, while for coarser particles such as fine silt and coarse silt was 50 and 80% removal efficiencies, respectively.

Key words: compost, biofilter, stormwater, treatment, construction sites

Introduction

Construction activities have significant potential to cause water pollution and stream degradation in areas under urban development if erosion and sediment control measures are not implemented properly. These activities could be considered a major source of sediment due to heavy land disturbance. Soil loss rates from construction sites can be 10 to 20 times that of agricultural lands (U.S. EPA 2000). The soil erosion rate from construction sites can range from minor amounts to 224 t·ha\(^{-1}\)·yr\(^{-1}\) depending on climate, soil type, slope, and best management practices (NCDENR 2000). Runoff originating in construction sites may have a turbidity range of several hundreds to several thousands nephelometric turbidity units (NTU) despite use of proper management practices (Minton and Benedict 1999).

Compost from Canadian sources has not yet been tested for its effectiveness in stormwater runoff treatment since using compost as a biofilter for removal of suspended sediments, and sediment-bound contaminants from stormwater runoff is a relatively new idea. The objectives of this research on compost biofilters was to: 1) determine through-flow capacity of the biofilter for hydraulic design of the system; 2) determine the effectiveness of the biofilter in removal of suspended sediments from stormwater runoff near construction sites; and 3) determine the longevity of the biofilters.

In 2000, a workshop presented by the Great Lakes Science Advisory Board assessing the status of nonpoint source pollution control in the Great Lakes basin identified that construction sites are significant sources of sediments to urban streams (Clarifica Inc. 2004). If left unchecked, runoff pollution from urbanizing watersheds, especially from construction sites, will increase sediment loads to receiving watercourses. To develop a sustainable solution for this problem, industries, governments, and nongovernment organizations in Ontario are in the process of evaluating and updating design criteria for controlling sediment transport in urban areas under development (Bradford and Gharabaghi 2004; Gharabaghi et al. 2006a).

Fish are highly sensitive to sediment-laden waters. Excessive turbidity blocks sunlight penetration, reducing photosynthesis by algae and aquatic plants and thus food production for aquatic life (Henley et al. 2000). Suspended sediments provide surfaces upon which other contaminants such as heavy metals and chemicals can be adsorbed (Clark et al. 2003). Total suspended solids (TSS) concentrations are often used as an indicator of stream water quality (OMOE 2003).

Sediment Control Measures

The most common soil erosion and sediment control measures used on construction sites include rock check dams, silt fences, triangular silt dykes, baffles, straw mulching, sediment basins/traps, and skimmers. Factors such as the intensity and duration of storm events,
A study conducted by Schueler and Lughill (1990) indicated that the TSS measured in runoff from construction sites were almost four times greater than the median value for varying storm conditions. They observed a removal efficiency of 46% of incoming sediment in outflows of sediment trapping devices, which was considered low due to the fine size of incoming sediment loads. Line and White (2001) monitored concentrations of TSS in outflow of three temporary sediment traps on two North Carolina construction sites, and observed sediment trapping efficiencies of 59 to 69% for sediment. Although these measures reduce the amount of pollutants entering the streams, they generally do not meet the required guidelines and standards (MOEE 1994).

According to Ward et al. (1979), trapping efficiencies greater than 90% are needed to meet typical water quality standards, but this efficiency is seldom attained. The European Inland Fisheries Advisory Commission (EIFAC 1965) reported that TSS concentrations above 80 mg/L are harmful to fish, and concentrations below 25 mg/L are tolerable. While several options exist to remove suspended solids from runoff, wet ponds are one of the common types of stormwater management systems in Ontario (OMOE 2003; Gharabaghi et al. 2006b). Settling is the primary mechanism for removal of TSS in construction sediment ponds, although physical and biochemical flocculation can be significant between rainfall events or during long residence times within ponds (OMOE 2003). According to the Ministry of the Environment's Stormwater Management Planning and Design Manual, treatment targets for post-construction stormwater ponds typically range from a minimum 60% removal to 80% removal of suspended solids (OMOE 2003).

A silt fence is a sediment-trapping practice utilizing a geotextile fabric (Tyler 2001) which is designed to increase the ponding depth (Goldman et al. 1986) to allow coarse sediment particles to settle out of storm runoff before it passes through the sediment barrier. Ponding depths increase as the silt fence geotextile becomes increasingly clogged by eroded sediment particles (Kouwen 1990). Barrett et al. (1998) concluded that effective sediment trapping by silt fence is not due to filtration by the fabric, but rather as a result of particles settling during detention behind the silt fence. Under low flow conditions, silt fences usually function well, but excessive runoff or ponding may lead to failure of the silt fence due to slumping and overtopping (Keener et al. 2006).

Compost Biofilters

Compost is commonly used for soil amendment, topdressing, and for erosion control, slope stabilization, and vegetative establishment applications (Faucette et al. 2005). Ettlin and Stewart (1993) found that yard waste compost can be used for slope stabilization and erosion control for slopes up to 42%. Yard waste compost was used in residential construction projects for erosion control and exhibited reduced sediment loads and improved water quality over conventional erosion and sediment control measures (Portland Metro 1994). Other compost related researchers (Michaud 1995; Demars and Long 1998; Glanville et al. 2001) reported that compost and mulch application has the capability to enhance the efficiency of existing erosion control management practices.

A new technology uses large volumes of compost material in mesh tubes also known as “socks” (diameters from 8 to 24 inches [20 to 61 cm]). These mesh tubes are very flexible multifilament polypropylene socks which are placed perpendicular to runoff for stormwater runoff treatment and sediment control (U.S. EPA 2006). In addition to ponding stormwater, these compost biofilters allow the water to flow through their three-dimensional matrix and filter it as water seeps through the organic media. The compost biofilter is designed to have a significant flow-through rate to reduce the chance of overtopping and water loss from under, or around, the compost biofilter.

After its lifetime, compost biofilter will be transported back to the composting facilities for recycling the contaminated sediments that were trapped in the biofilter. The sediments will be sieved out and properly disposed in a landfill. However, the compost media may be suitable for recycling through the composting facility.

The use of compost as a biofilter for treatment of stormwater runoff (as a through-flow medium to remove contaminants) is a relatively new idea. Ettlin and Stewart (1993) reported that compost filter berms improved sedimentation of TSS by 83% relative to bare soil, and by 72% relative to a silt fence over 5 natural rainfall events on a 34% slope. Additionally, the compost filter berm reduced TSS concentrations by 93% relative to bare soil, and by 91% relative to a silt fence. The U.S. Environmental Protection Agency (U.S. EPA 1997) tested a compost biofilter made of specially tailored leaf compost and reported a sediment removal efficiency of 90%, oil and grease removal efficiency of 85%, and heavy metals removal efficiency of 82 to 98%.

In another study at Ohio State University, flow-through rates of compost filter socks and a silt fence were evaluated, using a sediment-laden runoff concentration of 10,000 mg/L, containing only clay and silt, on a 20 degree slope for 30 minutes. The results showed that runoff flow-through rates of compost filter socks on average were 50% greater than the silt fence, and the ponding height behind a 24-inch (61-cm) silt fence was 75% greater than a 12-inch (30.5-cm) compost filter sock (Keener et al. 2006).
Materials and Methods

Beginning in the spring of 2006, laboratory and field experiments were conducted at the University of Guelph, School of Engineering, and the Turf Grass Institute, to evaluate the effectiveness of the compost biofilters in removing suspended sediments from stormwater runoff. The compost was essentially made of various yard wastes including leaf, twigs, bark, and wood chips, and was provided from three major compost producers in southern Ontario: the Region of Peel, the Region of Waterloo, and Alltreat Farms. In this study we specifically used the coarser compost material by presieving the compost using a 0.5-inch (1.27-cm) sieve (also known as the “overs”) to allow for higher flow-through capacity.

Physical Tests on Compost Material

Three representative samples per type of compost for a total of nine samples were tested for particle size distribution using an automatic shaker and a stack of varying numbered sieves, including sieves numbered 1 to 200. The void space was determined by placing 1,000 mL of compost into a graduated cylinder. Water was added to the cylinder to fill all the void spaces. The volume of water used to fill the spaces is equal to the volume of void spaces. Measurements were repeated three times and were done immediately after addition of water to the cylinder to prevent water being absorbed into the particles.

Flow-Through Tests

Flow-through tests were conducted to evaluate the flow-through capacity of the biofilter for the hydraulic design of the system. For this purpose, flow of the water passing through the filter sock under various hydraulic heads was measured. Figure 1 shows the flume used for flow rate tests. The flume was 1.5-m long by 0.69-m wide and 0.3-m deep with a constant head tank at the inlet end and a collection channel at the outlet. A prefilmed and measured compost sock of 8-inch (20-cm) diameter was placed into the outlet of the flume and secured snugly along the bottom and sides of the flume. This was done to minimize the amount of water that exits without passing through the compost filter. Water was evenly distributed by using the water taps in the lab. Water depth was measured directly upstream and downstream of the compost sock. The upstream measurement was essential to obtain consistent flow rate. If the depth did not change for a period of five minutes, it was assumed that steady state had been reached and a flow measurement was taken.

To take a flow measurement, the pump was turned off and the siphon was broken manually by moving the pipe around. A stopwatch was used to determine the flow rate over a one minute period. The pump was then turned back on to drain the water from the bucket and the measurements were repeated two more times, for a total of three, at every constant depth.

Fig. 1. a) Flume for flow rate testing, b) side view of the flume, and c) schematic drawing of the flume used for flow rate testing.
To achieve variable depths, the taps were turned down in stages to allow for readings at every 5- to 10-mm decrease in water depth. This test was performed three times for each compost type, with each run using a different sample, to account for the variability of the compost material.

Clean Water Tests

Compost filter tubes were subjected to clean water tests to determine if the biofilter would have an adverse effect on water quality due to wash-off of the compost material out of the sock. Clean water tests were performed in the same flume that was used for flow-through tests with the same setup. During the flow-through tests, samples were taken from the outflow water. The pH, TSS, turbidity, electrical conductivity, total Kjeldahl nitrogen, total phosphorous, and total organic carbon of the water filtered by the biofilter were all tested. The pH and conductivity measurements were done using digital readout probes. Turbidity was measured using a HACH 2100P Turbidimeter. TSS were measured according to the American Society for Testing and Materials standard method D3977-97C (ASTM 1999) using a 0.45-micron filter paper. Total Kjeldahl nitrogen, total phosphorous and total organic carbon were measured in the Soil & Nutrient Laboratory of University of Guelph using standard methods (APHA et al. 1992). Measured concentrations were compared with the Ontario Ministry of the Environment objectives (MOEE 1994) to evaluate their suitability for discharge to receiving waters.

Field Experiments

Field experiments were conducted in the summer of 2006 at the Guelph Turf Grass Institute, University of Guelph, to evaluate sediment removal efficiency of biofilters. Compost type, number of socks, sock diameter, and flow rate were tested to determine their effect on sediment removal efficiency. In the initial setup, two 10-m long, 1.2-m wide channels were constructed beside each other and were called plot A and plot B. Figures 2 and 3 present a picture and a schematic drawing of the plots. Initially, the sod layer was removed in the two plot sites and the ground was levelled. An end channel was constructed using sheet metal formed into a triangular spout with upright walls to direct the water. Sheet metal walls were then placed upright and perpendicular to each other to form the water column. The channels were then covered in plastic sheet wrap.

Water was supplied using a large constant head tank. In order to make synthetic stormwater runoff, a high clay content soil (approximately 50%, according to Fig. 2) was dried, grounded, and sieved. For each run a soil-slurry was prepared by mixing a 2-kg mass of sieved soil with 40 L of clean water in a mixing column. The prepared slurry was mixed with the clean water and was delivered at the inlet of the channel at a set rate using peristaltic pumps into a 1.2-m wide perforated polyvinyl chloride pipe where it was first diluted and then well mixed with the steady-rate inflow of clear water at the weir box (used to distribute flow evenly across the plot) upstream of the plots. The target influent TSS concentration was 850 to 900 mg/L, which is consistent with the monitoring data collected in collaboration with the Toronto and Region Conservation Authority from previous studies on construction sites in the Greater Toronto Area (Gharabaghi and Fata 2006).

New filter tests were conducted in plot A. After the initial setup, three sets of compost biofilters were placed...
along the plot after constructing a three tier/level using plywood and gravel. Five 8-inch (20-cm) socks were placed on each tier for a total of fifteen socks (Fig. 3). Six runs were conducted on each sample of compost. Each run started with about 30 minutes of clear flow to establish steady state conditions followed by 30 minutes of turbid-water flow. Samples were collected towards the end of the run. Four samples were taken from each sampling location (I, Z, K, and O; Fig. 4) for a total of sixteen samples from each run. Then five 18-inch (45-cm) socks were placed at the bottom of the run, and flow rates of 0.5, 1.0, 1.5, and 2.0 L/s were tested with two runs per flow rate. Four samples were collected from each of the input and output locations.

Plot B was used to test the overall longevity of the system. Peel, Waterloo, and Alltreat compost biofilters were placed on the first, second, and third tiers respectively. Seventeen runs were performed and four samples were taken from each sampling location (Fig. 3) per run. The second longevity test performed on Plot B consisted of running 30 consecutive runs using five 18-inch (45-cm) socks filled with Alltreat compost. Flow had a constant value of 1 L/s during the longevity tests. Again, four samples were collected at each location. A summary of test data is presented in Table 1.

Runoff Sample Analysis

The TSS for runoff samples were analyzed in the fluids lab of the School of Engineering in the University of Guelph according to ASTM standard method D3977-97C (ASTM 1999). Three samples out of a total of four collected at each location were used in TSS measurement. Statistical analysis was conducted on sediment removal efficiencies by using PROC MIXED within Statistical Analysis Software (SAS) version 9, which fits a variety of mixed linear models to data and enables statistical inferences about the data. The response variable was outlet sediment removal efficiency. The four fixed-effect treatments were sock size, compost type, number of socks, and flow rate.

![Fig. 4. Schematic drawing of plots including sample collection sites (I, Z, K, and O).](image-url)

<table>
<thead>
<tr>
<th>Plot</th>
<th>Sock size [inch (cm)]</th>
<th>Compost type</th>
<th>Average TSS concentration of influent (mg/L)</th>
<th>SD²</th>
<th>Average TSS concentration of effluent (mg/L)</th>
<th>SD</th>
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<tr>
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<td>8 (20)</td>
<td>Waterloo</td>
<td>992</td>
<td>214</td>
<td>495</td>
<td>201</td>
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<tr>
<td>A</td>
<td>8 (20)</td>
<td>Alltreat</td>
<td>837</td>
<td>289</td>
<td>456</td>
<td>197</td>
</tr>
<tr>
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<td>972</td>
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<td>628</td>
<td>128</td>
</tr>
<tr>
<td>A</td>
<td>18 (45)</td>
<td>Waterloo</td>
<td>906</td>
<td>103</td>
<td>369</td>
<td>95</td>
</tr>
<tr>
<td>A</td>
<td>18 (45)</td>
<td>Alltreat</td>
<td>838</td>
<td>141</td>
<td>400</td>
<td>85</td>
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<tr>
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<td>Peel</td>
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<td>156</td>
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<tr>
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<td>Alltreat</td>
<td>853</td>
<td>152</td>
<td>490</td>
<td>96</td>
</tr>
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</table>

*SD = standard deviation.*

75
Using a particle size analyzer (Mastersizer 2000), the fourth sample taken from each of the runs was run through the machine to verify any trends in the particle size distribution of each sample. The Mastersizer works by using the optical unit to capture the actual scattering pattern from a field of particles. It then calculates the size of the particles that create the pattern using the Fraunhofer model as well as the Mie theory.

Results and Discussion

Physical Tests

Figure 5 shows the average particle size distribution of the three compost types. Approximately 92 to 99% of compost particles passed through a 25.4-mm sieve, 82 to 94% passed through a 19-mm sieve, and 58 to 84% passed through a 9.42-mm sieve. The calculated uniformity and gradation coefficients both show that the composts are fairly well graded. For all three samples, void spaces ranged from 60 to 70%. All three compost types showed similar trends during the flow-through tests. Figure 6 displays the results of the flow rate tests after averaging for all replications. The average flow-through capacity per unit width of the 8-inch (20-cm) sock for the three compost materials without overtopping was 1.5 L·s⁻¹·m⁻¹. The flow-through capacity without overtopping of the 18-inch (45-cm) sock was approximately double the flow-through capacity of the 8-inch (20-cm) sock. Considering that the 8-inch (20-cm) sock when installed flattens to an oval shape with a height of about 14 cm, the seepage flow-through velocity was approximately 0.01 m/s.

Clean Water Tests

Clean water tests were conducted by measuring the TSS, pH, turbidity, electrical conductivity, total Kjeldahl nitrogen, total phosphorous, and total organic carbon. The suspended solid concentrations of the Alltreat and Waterloo composts were quite similar. Peel had slightly higher TSS concentration in the first 30 minutes. This is likely due to the release of fine particles.

Figure 7 displays these results clearly. To meet the target water quality guideline for the protection of aquatic life, TSS should have a threshold value of 25 mg/L for chronic exposure, and 80 mg/L for acute short-term exposure (OLFAC 1965). As shown in Fig. 7, a 10-min flush period will be required to meet these guidelines for short-term exposure.

Turbidity was also similar for all three compost types. After the first 10 minutes all turbidity approached zero (Fig. 8).

The pH of runoff met the Provincial Water Quality Objectives set by the Ontario Ministry of Environment and Energy (MOEE 1994), and was well within the 6.9 to 7.2 range. Results for total Kjeldahl nitrogen showed that concentrations approached zero after about 5 minutes.
of clean water wash. Total phosphorous concentrations dropped below the detection limit (0.050 mg/L) after about 5 minutes of clean water flush through the biofilter. For total organic carbon, the three different composts followed the same trend, as shown in Fig. 9. After about 5 minutes of clean water wash, the concentrations ranged between 0 and 7 mg/L.

Field Experiments

Field experiments were divided into two categories. The first experiment examined the effect of sock size, number of socks, compost type, and flow rate on the removal efficiency of the biofilters. The second experiment investigated performance of the biofilter as void spaces became increasingly filled with sediment over time. A total number of 318 samples were taken during the first experiment, and 492 samples were taken during the second experiment. All samples were analyzed for TSS. The effect of number of socks and compost type on sediment removal efficiency for 8-inch (20-cm) socks is shown in Fig. 10.

Statistical Analysis

Using Statistical Analysis Software (SAS), data from experiment 1 were analyzed and a linear mixed model was chosen to study the effects of four factors on sediment removal efficiency. These factors included sock size (8 or 18 inches [20 or 45 cm]), compost type (Waterloo, Alltreat, or Peel), number of socks (5, 10, or 15) and flow rate (0.5, 1, or 2 L/s). The outlet sediment removal efficiency was calculated as the ratio of sediment concentration difference (inflow/influent – outflow/effluent) over the inflow/influent concentration.

The linear mixed model for experiment 1 includes the above four treatments, and their interaction as a fixed effect. The date and the run number are taken as random blocks to further reduce error. The residuals of the final model are normally distributed. The model was simplified by removing those nonestimable interactions and nonsignificant main effects. Details for calculations of the statistical analysis to determine the significance of each fixed effect on sediment removal efficiency are presented in Table 2. It was found that while sock size and number of socks had a significant effect on sediment removal efficiency, the compost type and flow rate did not. The flow rate is typically an important parameter, but over the narrow range of flow rates tested (0.5 to 2 L/s), the effect on removal efficiencies was not significant.

The model was also used to estimate the mean removal efficiency of different combinations of number of socks and sock sizes. The estimated mean removal efficiencies and 95% confidence intervals are presented in Table 3. For the 8-inch (20-cm) sock size, the mean removal efficiency increased linearly from 34 to 60% as the number of socks increased. The same condition applies to the 18-inch (45-cm) sock size; the removal...
efficiency increased linearly from 69 to 95% with the number of socks increasing from 5 to 15.

Experiment 2 was conducted to study the longevity of different types of socks and determine their approximate life expectancy. The treatments involved were the same as in experiment 1, except the flow rate was fixed at 1 L/s. Longevity test results for five socks of both 8 inches (20 cm) and 18 inches (45 cm) are presented in Fig. 11. The data from experiment 2 were analyzed by fitting separate time curves for different treatment combination groups. The response variable is the outlet sediment removal ratio. In this experiment, the treatment flow rate was fixed at the 1 L/s level, so we examined three fixed-effect treatments of sock size, compost type, and number of socks in our model. According to the analysis results, it was concluded that the time trend is best described by a quadratic curve, indicating that the removal efficiency decreases very fast for the first several runs, but gradually stabilizes at a certain level. Based on the model, the estimated mean and 95% confidence interval for 5, 10, 15, and 20 runs is presented in Table 4. There were only 17 runs for the 8-inch (20-cm) sock size group, which makes the prediction unreliable for the 15th and 20th runs; therefore, mean removal efficiencies for 8-inch (20-cm) socks were estimated for up to 10 runs. For 18-inch (45-cm) socks, having five socks, the expected removal efficiency decreased to approximately 25% after 20 runs, with range of 49 to 59% at the 95% confidence level.

**Particle Size Distribution Effect**

The particle size distribution for inlet and outlet samples was measured with the Mastersizer instrument, and the results are presented in Fig. 12. Sediments were classified into four particle size classes: class 1 consisted of particles finer than 5.75 μm (clay size particles), class 2 consisted of particles between 5.75 and 20 μm (fine silt), class 3 consisted of particles between 20 and 60 μm (coarse silt), and class 4 consisted of particles larger than 60 μm (fine and medium sand). Removal efficiency at each point was calculated for all four classes. Table 5 presents the mean removal efficiency for different sediment particle size classes. Sediment removal efficiency was about 38% for clay size particles (class 1), about 44% for fine silt (class 2), 67% for medium silt (class 3), and 34% for coarse silt (class 4). According to the U.S. EPA (1993), other sediment control measures, particularly silt fencing, remove less than 20% of silt and clay from the stormwater, while Barrett et al. (1993) observed that 92% of TSS were clay and silt. Therefore, the capability of compost biofilter in removing 38 to 70% of clay and silt particles further highlights its effectiveness in removal of fine particles from stormwater.
Conclusions

The following concluding remarks are based on the laboratory and field experiment results on compost biofilters:

- The seepage flow velocity through compost media was about 0.01 m/s. That is, the flow-through capacity (without overtopping) per unit cross-sectional area perpendicular to the flow direction for the three compost materials (overs) tested was approximately 10 L·s⁻¹·m⁻².
- The flow-through capacity of the 18-inch (45-cm) socks was approximately 200% higher than the flow-through capacity of the 8-inch (20-cm) sock. That is, the seepage flow velocity was roughly the same at 0.01 m/s.
- Sediment removal efficiency increased with the number of socks; the average sediment removal efficiency of the 8-inch (20-cm) socks for 5, 10, and 15 rolls were 34, 48, and 60%, respectively.
- Larger diameter socks provided larger filter media and were more effective than the smaller diameter socks. The average sediment removal efficiency of the 18-inch (45-cm) socks for 5, 10, and 15 rolls were 69, 84, and 95%, respectively.
- The sediment removal efficiency reduces significantly over time. The average sediment removal efficiency of 5 rolls of the 18-inch (45-cm) sock steadily and gradually reduced from 70 to 62, 58, 56, and 54% after 1, 5, 10, 15, and 20 consecutive runs.
- Sediment removal efficiency did not depend on flow rate as long as the stormwater runoff did not overtop the biofilter.
- During the field experiments, for a range of 765 to 1,022 mg/L influent TSS concentrations, the effluent TSS concentrations ranged from 369 to 628 mg/L.
- Particle size distribution is an important design factor for the biofilter. Sediment removal efficiency of clay size material was about 38% while for fine silt it was around 44%, and for medium and coarse silt the removal efficiency was around 67%.

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References


TABLE 5. Mean removal efficiency for different sediment particles size classes

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<td>44</td>
<td>67</td>
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* Class 1: 0.1 μm < d < 5.754 μm; Class 2: 5.754 μm < d < 19.953 μm; Class 3: 19.953 μm < d < 60.256 μm; Class 4: 60.256 μm < d < 1,096 μm.

Fig. 12. Particle size distribution of inlet and outlet samples. Class 1: 0.1 μm < d < 5.754 μm; Class 2: 5.754 μm < d < 19.953 μm; Class 3: 19.953 μm < d < 60.256 μm; Class 4: 60.256 μm < d < 1,096 μm.

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