Comparing Properties of Water Absorbing/Filtering Media for Bioslope/ Bioswale Design

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Drainage from highways, particularly the first flush of runoff, contains high levels of contaminants such as suspended solids, metals, and organics. To restrict the discharge of polluted stormwater, the National Pollutant Discharge Elimination System (NPDES) State Disposal System (SDS) General Permit issued by Minnesota Pollution Control Agency (MPCA) in 2013 requires that the first inch of stormwater runoff from new impervious should be held on site through infiltration, harvesting or reuse. Multiple types of infiltration materials have been studied in the laboratory and the field, but few studies have considered the application of local materials for best management practices (BMP). The objective of this project is to determine the characteristics of various naturally occurring water adsorbing and filtering media, such as peat and muck, found along road construction projects in northern Minnesota. Salvage and reuse of these materials during road construction will be evaluated for stormwater treatment, including absorption, infiltration, filtration, and pollutant capture, in constructed vegetated slopes along highway right of ways. The naturally occurring material will be compared to leaf and grass feedstock compost.

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FINAL REPORT

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EXECUTIVE SUMMARY

Under the National Pollutant Discharge Elimination System (NPDES) State Disposal System (SDS) General Permit issued by the Minnesota Pollution Control Agency (MPCA), the Minnesota Department of Transportation (MnDOT) is required to retain the first inch of highway stormwater runoff. The University of Minnesota Duluth (UMD) Natural Resource Research Institute (NRRI) received two years of funding from MnDOT for the project *Comparing Properties of Water Absorbing/Filtering Media for Bioslope/Bioswale Design* to evaluate the water absorbing, filtering, pollutant capture, and plant growth properties of natural media for application in bioslopes and bioswales along state highways. In northeast Minnesota, reuse of road construction waste products, such as peat and muck soils, combined with taconite tailings (sand-sized mining byproduct) could provide a suitable media for biofiltration treatment of stormwater that meets NPDES goals, improves best management practices (BMPs), and potentially reduces construction costs.

The characteristics of these materials, such as peat and muck, and their potential salvage and reuse with taconite tailings or sand were evaluated for utilization in constructed vegetated slopes along highway right of ways in northeast Minnesota.

Current MnDOT specifications that require filtration media include a mix of between 60 – 80% sand with the remainder made up of organic compost that is either added to the sand or applied as a blanket. Peat and muck have also been studied for use as soil amendments. Peat provides better hydraulic properties, providing both capture and filtration of water and pollutants, and supports vegetation growth. Study of muck as a filtration media is limited. In October and November 2015, our team identified and collected compost from the Western Lake Superior Sanitary District (WLSSD), salvaged peat and muck from Hwy 53 Tini pit, taconite tailings from ArcelorMittal, commercial peat from Premier Horticulture, and sand from Solway Township. These materials were used in our laboratory characterization and field pilot test.

A suite of laboratory methods for characterizing treatment materials to test physical, chemical, and biological properties of collected materials was developed. Tests were selected based on a review of the literature. The three main objectives of the tests were: (1) to classify the study materials for aiding in the reproducibility of the study results; (2) to define the properties of the individual study media in order to predict their performance when applied *in-situ*; and (3) to inform the development of filter media mix designs that optimize the stormwater treatment performance in bioinfiltration BMPs. Infiltration rates were measured using saturated hydraulic conductivity as measured in the falling head test. Batch and column leaching experiments were used to quantify pollutant (copper, lead, zinc, nitrate, phosphate) removal efficiency of single and mixed materials. Bioassays and greenhouse studies were used to evaluate plant growth on the substrates and mixes.

Various material combinations were tested using the above methods, and based on the results, pilot scale testing was initiated. Pilot field tests were installed along NRRI's parking lot and include three plots containing a 50:50 peat and sand mixture, and another three plots with a 50:50 compost and sand mixture. Water infiltration, discharge water quality, and vegetation establishment were monitored between April and August 2017.

The findings from the laboratory and field pilot tests are summarized based on three disciplines: civil engineering, environmental engineering, and biology.

CIVIL ENGINEERING

The primary civil engineering design requirement was infiltration rate. Because the saturated condition represents the worst-case scenario, saturated hydraulic conductivity was used as a measure of infiltration rate and, therefore, water holding capacity. A minimum requirement of $1.5*10^{-4}$ cm/sec was determined from testing media based on current MnDOT specifications for bioslope and bioswale design (40 – 60% commercial compost mixed with sand). Laboratory results showed that muck had unacceptably low hydraulic conductivity. Peat performed at least as well as compost in terms of saturated hydraulic conductivity and other important hydraulic and geotechnical considerations. Additionally, taconite tailings and sand were interchangeable from a civil engineering perspective. Initial data from pilot field tests showed the two mixes (50:50 mix of peat and sand, 50:50 mix of compost and sand) had similar water storage capacity.

Results from this project show that the saturated infiltration rate as measured using the falling head test best predicts a biofilter media mixture's ability to meet civil engineering requirements. In summary, mixtures composed of 40 – 60% peat with the remainder composed of either sand or taconite tailings compare favorably with current MnDOT specifications for bioslope and bioswale design. It is important to note, however, that due to the variability of materials, not all peat or taconite tailings will behave the same.

ENVIRONMENTAL ENGINEERING

The environmental tests of salvaged filtration materials quantified pollution retention capacities of each material under steady or dynamic conditions. Under steady conditions, salvaged peat, compost, and commercial peat performed well, with high metal (copper, lead, and zinc) retention capacities, generally over 80%, and the difference among these materials was small. Muck can adsorb around 50% of metals. In contrast to the high removal efficiencies for metals, these organic materials did not remove nutrients, especially compost, which released a significant amount of nitrate and some phosphate.

The release of phosphate from compost was also observed in column leaching experiments and the field pilot test. More than 1000 µg/L phosphate was exported from compost columns or field pilots containing compost. In addition, average metal removal efficiencies by compost were around 83% for copper and zinc, which were significantly lower than metal removal efficiencies by salvaged peat (more than 98%) under dynamic conditions.

Taconite tailings showed the potential to remove phosphate, especially under slightly acidic conditions (pH around 6). Commercial peat produced acidic outflow, and the combination of commercial peat with taconite tailings led to outflow phosphate concentrations of around 10 µg/L.

Overall, salvaged peat had better pollutant remove efficiencies than compost. Taconite tailings can be used to replace sand to enhance potential phosphate removal.

BIOLOGY

Compost and peat both performed well in mixtures with sand and taconite tailings in providing a viable substrate for plant growth. Media mixes containing compost, especially at 25% compost, performed the best in plant growth trials. Muck was difficult to mix with any other media and its value for plant growth was minimal. Greenhouse study results showed little to no significant effect of sand vs. tailings on plant growth response. However, replacing compost with peat resulted in reduced plant growth with increasing amounts of peat. This could be remedied with additions of supplemental phosphorus and potassium fertilizer, as these were shown to be deficient in the nutrient analyses.

The MnDOT Suitability to Grow test and Solvita® tests have the potential for rapid analysis of media, and in most cases, predicted success in the greenhouse trials. The exception was the Suitability to Grow test for compost, which gave false negative results. The seed germination and plant growth greenhouse trials and nutrient analysis provided the most information on potential treatment media success in supporting plant establishment and growth.

Both peat and compost support plant establishment and growth. Due to documented variability in peat's properties depending on origin and degree of decomposition, it may be prudent to evaluate peat materials on a case-by-case basis when used in stormwater treatment devices. Sand and tailings are interchangeable from a plant growth perspective.

RECOMMENDATIONS

This project demonstrated that peat has high potential to replace commercial compost in MnDOT standard bioslope and bioswale design. Additionally, taconite tailings performed comparably to the sand currently specified in MnDOT designs. Results from this project showed that muck has little potential to replace commercial compost or peat due to low permeability and infiltration capacity, filtration, and plant growth support. Finally, a pilot field study established good agreement between laboratory results and field measurements for the 50:50 peat-sand mixes, as well as comparing performance between peat-sand mixes and compost-sand mixes.

Finding alternatives to commercial compost and sand would help MnDOT meet regulatory requirements as well as reduce purchase and shipping costs and the need to transport and store excavated material from rural road construction sites. This project exhibits the potential to use what was previously waste material in a beneficial manner.

CHAPTER 1: INTRODUCTION

Drainage from highways, particularly the first flush of runoff, contains high levels of contaminants such as suspended solids, metals, and organics. To restrict the discharge of polluted stormwater, the National Pollutant Discharge Elimination System (NPDES) State Disposal System (SDS) General Permit issued by the Minnesota Pollution Control Agency (MPCA) in 2013 requires that the first inch of stormwater runoff from new impervious should be held on site through infiltration, harvesting, or reuse. Multiple types of infiltration materials have been studied in the laboratory and the field, but few studies have considered the application of local materials for best management practices (BMP). The project team sought out treatment media sources in close proximity to current and future highway construction projects in MnDOT District 1 in northern Minnesota using published maps, geotechnical soil boring reports, and in coordination with MnDOT staff. Media include salvaged peat, muck, commercially available peat from approved sources, and taconite tailings.

The objective of this project was to determine the characteristics of various naturally occurring water adsorbing and filtering media, such as peat and muck, found along road construction projects in northern Minnesota. Salvage and reuse of these materials during road construction was evaluated for stormwater treatment properties, including absorption, infiltration, filtration, and pollutant capture, in constructed vegetated slopes along highway right of ways. The naturally occurring materials were compared to leaf and grass feedstock compost. Based on the characterization results, suggestions for testing, design, implementation, and monitoring protocols for construction of an in-field pilot study will be developed for bioslopes and bioswales.

The comprehensive literature review assembled examples of stormwater treatment utilizing bioslope/ bioswale in practice, BMPs, and construction methods. The researchers focused on local, state, and federal regulations to ensure that examples apply to this project's area of interest. The literature review also revealed experiment protocol and material properties important in previous designs. Tests to determine relevant properties were chosen from currently standardized experiments or were tailored to the selected media. Laboratory experiments determined the biological, civil engineering, and environmental engineering properties of selected media and mixtures. All tests were either standardized (i.e., ASTM International (ASTM), Environmental Protection Agency (EPA), etc.) or designed in a manner to ensure repeatability. Evaluation concentrated on physical, chemical, and biological properties of selected peat samples, muck samples, and commercially available peat as compared to specified MnDOT compost products.

1.1 CIVIL ENGINEERING

Geotechnical characterization included soil classification, compaction, permeability, and strength. These properties were measured using standard ASTM or commonly accepted methods. Infiltration and water retention capacity were measured. This suite of tests was adapted to include lessons learned in the literature review.

1.2 ENVIRONMENTAL ENGINEERING

The study samples' chemical properties such as organic content, pH, metal and nutrient content were characterized in the Natural Resources Research Institute's (NRRI) analytical laboratories. In addition, samples were evaluated for effectiveness in removing chemicals (copper, lead, and zinc) and nutrients (phosphorus, nitrogen) in batch mixing and continuously flushing conditions. Testing included mixtures of organic materials, such as peat, compost, and muck, with inorganic materials, such as sand and taconite tailings. Laboratory-prepared solutions were utilized. Leachate from columns was collected to characterize contaminant removal efficiencies under dynamic conditions.

1.3 BIOLOGICAL

Potential treatment media must not only possess the proper physical and chemical characteristics to effectively treat water flow and contaminants but must also have the ability to grow and support vegetation. An initial inspection of potential treatment media "salvage" sites was conducted to evaluate any plant species present including introduced, native, invasive species, or noxious weeds. This gave a preliminary indication of media fertility and seed bank. Potential phytotoxic properties and the ability to grow plants were tested in germination studies at NRRI. Nutrient analyses were also conducted on organic materials to determine potential fertility. Based on preliminary results, germination and plant growth greenhouse studies were also conducted on media mixtures.

1.4 FIELD TEST

Based on laboratory testing results, the authors have provided recommendations for initial treatment system design. Project considerations, such as media application, site selection, material salvage/collection, construction methods, and re-vegetation, are suggested. A preliminary field pilot test is currently being conducted on a slope adjacent to the NRRI parking lot using the materials selected from laboratory testing results. The utilization of local salvage materials for stormwater treatment has potential implications for future green infrastructure development as well as reducing project cost.

1.5 REPORT ORGANIZATION

This project investigated the characteristics of studied filtration materials through laboratory and field pilot tests. The field application of these materials in stormwater treatment system is not included in this project but will be investigated in the next project. This final report begins with a background chapter (Chapter 2) to review the application of bioslopes and bioswales as stormwater treatment BMPs. Chapter 3 describes the sources of studied filtration materials and sample collections. Chapter 4 lists the methods to be used to quantify biological, civil, and environmental properties of filtration materials in the laboratory. The experiment results created by using methods described in Chapter 4 are presented in Chapter 5. Chapter 6 presents the design of the field pilot test and preliminary results. A general conclusion of this study is presented in Chapter 7.

CHAPTER 2: BACKGROUND

2.1 INTRODUCTION

This chapter provides context for the implementation of bioinfiltration BMPs such as bioslopes and bioswales for the treatment of stormwater runoff. The performance and factors affecting the performance of bioinfiltration BMPs are reviewed. Additionally, a review and synthesis of research related to filter media and soil amendments for improving water absorption, geotechnical properties, vegetative support, and pollutant capture in bioinfiltration BMPs is provided. This review also focuses on the beneficial reuse of waste materials readily available in northern Minnesota. These materials will be compared to compost, peat, muck, and taconite tailings.

2.2 OVERVIEW

The accumulation of pollutants on roadways can result in contaminated stormwater runoff that has a negative effect on receiving water quality, groundwater quality, and aquatic ecosystems (EPA, 1995). Pollutants accumulate on roadways via three primary mechanisms: atmospheric deposition, vehicle deposition, and maintenance activities (Barrett et al., 1995). Typically occurring roadway pollutants, presented in Table 2.1, include suspended solids, heavy metals, excess nutrients (nitrogen and phosphorus), deicing chemical constituents, pesticides, herbicides, petroleum byproducts, organic compounds, and bacteria. Median pollutant concentrations for highway runoff and discharge limits are also provided (Herrera Environmental Consultants, 2007).

Additionally, roadways increase impervious surface area resulting in an increase in runoff volume and peak discharge intensity. Increasing runoff volume and intensity can result in increased erosion and turbidity, which has been linked to negative impacts on water quality and public health (Gaffield, 2003).

During dry periods, pollutants accumulate on roadways until a precipitation event occurs. The initial precipitation mobilizes the built-up pollutants and washes them off the road surface in what’s known as “first flush” behavior (Kayhanian et al., 2012). First flush behavior implies that a majority of accumulated pollutants are washed off in a relatively small fraction of initial stormwater runoff. The well-documented occurrence of first flush behavior (Barrett, 1998; Bertrand-Krajewski, 1998; Deng, 2009; Gupta and Saul, 1996) has led stormwater management policy in the United States to focus on the treatment of the first inch of runoff, maintaining pre-development hydrology and protecting receiving waters.

Table 2.1. Typically occurring roadway pollutants, their sources, nationwide median concentrations in stormwater and Minnesota discharge limits (Barber et al., 2006; Clar et al., 2004; EWGCC, 2000; Herrera Environmental Consultants, 2007; Kobriger, 1984; MPCA, 2015; TRB, 2006; Yonge, 2000).

Pollutant	Source	Median Concentration	Water Quality Standards*
Total Suspended Solids	Pavement wear, vehicles, atmospheric deposition, maintenance activities, snow/ice control, sediment disturbance	78.4 mg/L	10 mg/L
Heavy Metals	Tire wear, atmospheric deposition, vehicle wear, motor oil, grease, rust, highway structures (bridges, guardrails), metal plating, insecticides and fungicides, lubricants, diesel fuel, gasoline, asphalt paving	Cu: 11.1 µg/L Pb: 50.7 µg/L Zn: 129 µg/L	At hardness = 50 mg/L **Cu:** CS = 6.4 µg/L, MS = 9.2 µg/L, FAV = 18 µg/L **Pb:** CS = 1.3 µg/L, MS = 34 µg/L, FAV = 68 µg/L **Zn:** CS = 59 µg/L, MS = 65 µg/L, FAV = 130 µg/L
Nitrogen and Phosphorus	Atmospheric deposition, fertilizer applications, dead plant material, road-kill, sediments, exhaust	TN: 2 mg/L TKN: 1.47 mg/L NO2+NO3: 0.533 mg/L TP: 0.259 mg/L TSP: 0.103 mg/L	TP = 12 – 150 µg/L depending on locations and types of rivers and lakes
Sodium and Chloride	Deicing salts	Cl- (MN): 116 mg/L	CS = 230 mg/L MS = 860 mg/L FAV = 1720 mg/L
Sulfates	Fuels, deicing salts		
Petroleum	Spills, leaks, hydraulic fluids, asphalt surface		
Polycyclic aromatic hydrocarbons (PAH)	Exhaust		
Pesticides and herbicides	Atmospheric deposition, spraying of rights-of-way, soils		
Polychlorinated biphenyl (PCB)	Atmospheric deposition		
Bacteria	Soil litter, wildlife waste, road-kill, trucks hauling livestock waste	570 – 6200 (Range of average total coliform, CFU/100 mL)	

*Class 2 Aquatic Life and Recreation (MPCA, 2015).

NOTE: Cu=copper; Pb = lead; Zn = zinc; TN = total nitrogen; TKN = total Kjeldhal nitrogen; TP = total phosphorus; TSP = total soluble phosphorus; Cl = chloride; CS = chronic standard; MS = maximum standard; FAV = final acute value.

2.3 POLICY AND REGULATIONS

In Minnesota, the construction of new impervious surfaces requires a “Construction Stormwater General Permit” issued in accordance with the NPDES. The NPDES Construction Stormwater permit is issued in compliance with the Clean Water Act of 1972 including more recent amendments which address stormwater directly (MPCA, 2013). The permit explicitly requires the retention and treatment of the first inch of runoff from new construction. Linear construction projects such as roadways present unique issues for achieving compliance due to the variety of land types encountered and limited “right of way” acquisition. Possible permitted solutions to these issues include bioinfiltration and bioretention systems such as bioslopes and bioswales (Stenlund, 2014a).

2.4 BEST MANAGEMENT PRACTICES: BIOSLOPES AND BIOSWALES

A bioswale is a vegetated channel designed to provide linear conveyance, retention, and water quality treatment of stormwater, pictured in Figure 2.1. A bioslope is a flat vegetated slope designed to provide sheet flow conveyance, retention and treatment of runoff, shown in Figure 2.2. Bioslopes and bioswales are often constructed as a treatment train series with the bioslope conveying sheet flow to the bioswale for linear transport, as pictured in Figure 2.3. Both provide water quality improvement by mass removal and concentration reduction (Barrett et al., 1998a). Mechanisms for treatment include volume reduction through infiltration into the soil, physical filtration by soil media, sedimentation, biological treatment by plant uptake and microbial action, and adsorption through interaction with soil components (Barrett et al., 1998a). A comparison by Claytor and Schueler (1996) of several BMP types found that bioswales and bioslopes provide moderate to high levels of removal for heavy metals, total suspended solids, and nutrients. The primary advantage of bioslopes and bioswales is the relatively low cost (Deletic, 2005) and feasibility of construction (Stenlund, 2014a).

Figure 2.1 A bioswale adjacent to a highway (California Department of Transportation (Caltrans), 2015).

Figure 2.2 Bioslope adjacent to a highway (Caltrans, 2004).

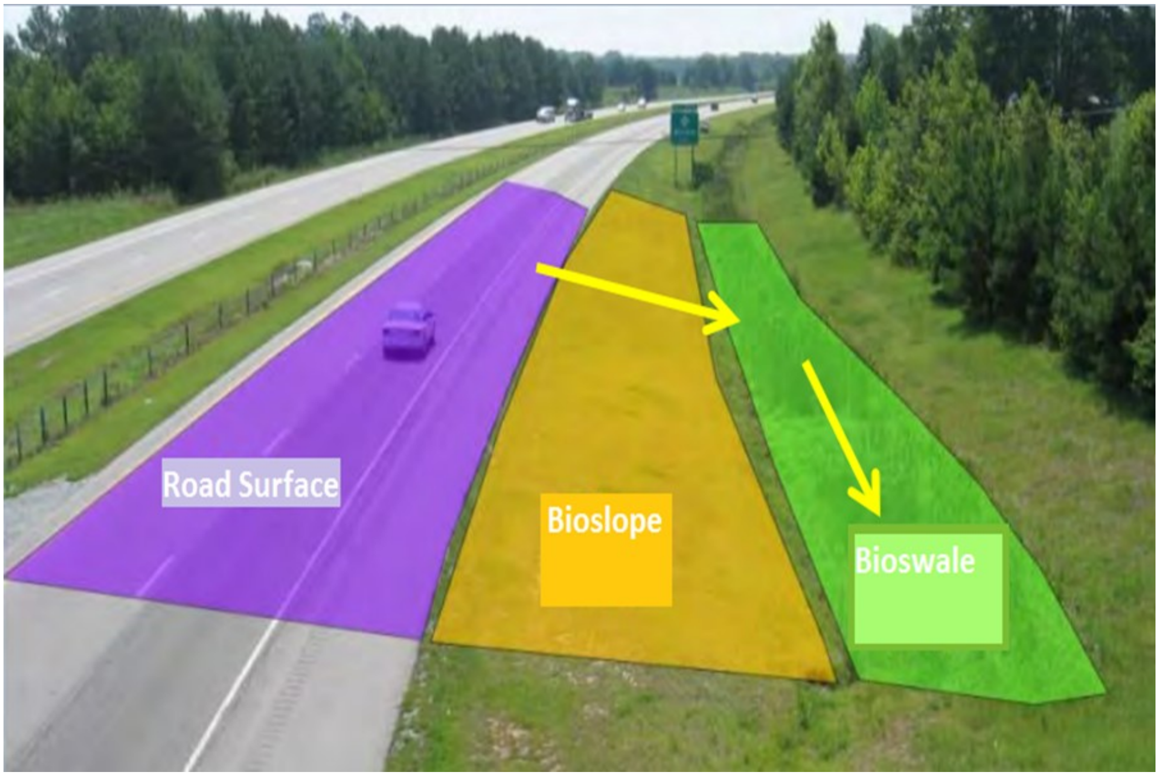


Figure 2.3 A highway bioslope and bioswale treatment train (adapted from North Carolina Department of Transportation, 2012).

2.5 POLLUTANT REMOVAL PERFORMANCE OF BIOSLOPES AND BIOSWALES

A review of the literature on the performance of bioslopes and bioswales for removal of pollutants shows that relative to cost these BMP options provide high levels of treatment. Commonly studied pollutants and removal efficiencies are summarized in Table 2.2.

High removal rates of suspended solids and moderate removal rates of metals indicate that bioslopes and bioswales can be used to effectively treat stormwater. In addition, a number of design factors have been found to exert control over the performance of these BMPs. Due to their effect on bioslope and bioswale performance, the optimization of these factors can provide enhanced stormwater pollution treatment abilities.

Table 2.2 Pollutant removal efficiencies from field studies of bioslopes and bioswales.

Reference	BMP Type	Removal Efficiency			
		Suspended Solids	Heavy Metals	Nutrients	BOD & COD
Backstrom, 2002	Bioswale	79 – 98%			
Barrett, 2004	Bioswale	60%	Total: Zn=62% Dissolved: Zn=24%	Total: 60% Dissolved: 40%	**
Barrett, 2004	Bioswale	86%	Pb=30%, Zn=87%	N=35%,TKN=39% P=38%	
Barrett et al., 1998b	Bioswale	85 – 87%	Zn=75%, Pb=17%, Fe=75%	Total P=34-44%, TKN=23 – 50%	COD= 61 – 63%
Barrett, 2004	Bioslope	72%	Total: Cu=80%, Pb=87%, Zn=80%; Dissolved:Cu=68%, Pb=7%, Zn=72%		
Biesboer and Elfering, 2004	Bioswale	50%, 70%*		TP=22%, ortho-P=42% 54%*,52%*	
Davis and Stagge, 2005	Bioswale	79%	Cu=46%, Pb=35%, Zn=50%	TKN=-2%, Nitrate=46% Nitrite=84%, Total P=-72%, Cl=-295%	
Deletic et al., 2009	Bioslope	35 – 90%		Ortho-P=5 – 50%, Solid N=35 – 90%, 14% for soluble N	
Yousef et al., 1987	Bioswale		35 – 93% depending on metal		
Yu and Kaighn, 1995	Bioslope	63.9%	Zn= 87.6%	-21.2 TP	59.3% COD

BOD = Biological Oxygen Demand, COD = Chemical Oxygen Demand
** = COD removal observed when influent concentration exceeds 80 mg/L,
* = after check dam installation

2.6 DESIGN PERFORMANCE FACTORS FOR BIOSLOPES AND BIOSWALES

Several design factors affecting the performance of biofiltration devices have been identified in the literature. These factors include the characteristics of the soil/ filtration media used, the characteristics of the vegetation selected, and the geometry or physical dimensions of the constructed bioslopes and bioswales (Barrett et al., 1998b). Infiltration rate, which is affected by runoff intensity and volume, initial moisture content, vegetation, geometry, compaction, maintenance, and soil media has emerged as an important controlling mechanism for the performance of biofilters (Ahmed et al., 2015; Gulliver et al., 2014; Hatt et al., 2008). In terms of upstream design variables, geometry, vegetation, and filtration media can all exert control over swale performance. Vegetation and filtration media hold the most potential for innovation and improved performance due to the broad variation in available plants and filter media materials and will therefore be the focus of this review.

2.6.1 Hydraulic Performance: Volume Reduction and Infiltration Capacity

The rate of infiltration in biofilters controls stormwater runoff volume reduction capacity, the exposure of pollutants to potential sorbents, the ability of the soil media to act as a physical filter, and the recharge of groundwater (Claytor and Schueler, 1996; Larson and Safferman, 2008; Emerson and Traver, 2008). Field infiltration rates have been found to be highly variable resulting in varying volume reduction capabilities in various biofilters (Yousef et al., 1987; Ahmed et al., 2015). Gulliver et al. (2014) provides a summary of swale volume reduction capabilities from several studies with a range of 9 – 100% reduction.

Despite this variability, when achieved, volume reduction has been found to be a consistent and reliable way to reduce pollutant mass loads to receiving waters even when pollutant concentration is unaffected (Pitt and McLean, 1986). Yousef et al. (1987) also found strong correlation between volume reduction and the nutrient removal capabilities of six swales, presented in Figure 2.4.

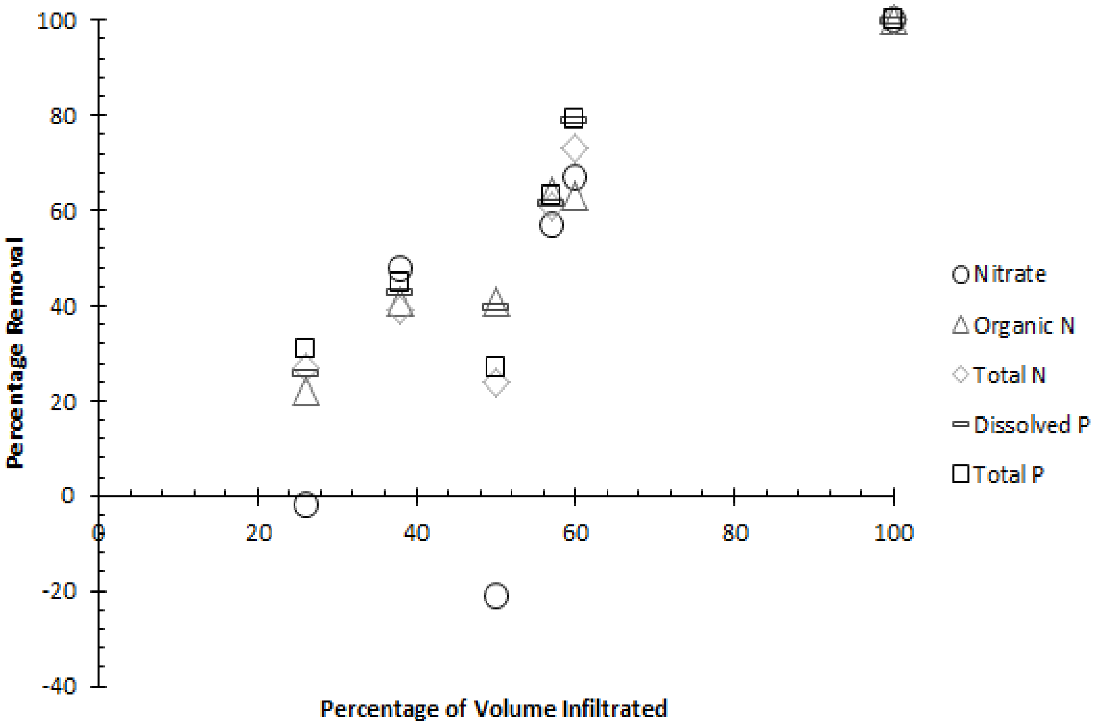


Figure 2.4 Percentage of pollutant removed versus volume infiltrated in bioswales (Yousef et al., 1987). Note: 100% volume reduction results in 100% removal of all pollutants.

The strong correlation between pollutant removal capability and volume reduction by infiltration has led several researchers to recommend infiltration rate as a key design parameter when designing biofilters (Abida and Sabourin, 2006; Backstrom, 2003; Claytor and Schueler, 1996). Barr Engineering Company performed a simulation of swale design parameters using the MPCA-designed MIDS calculator to assess the effect on annual volume reduction. Of the five parameters tested, infiltration rate exhibited the highest degree of control on annual volume reduction percentage. Channel length also exhibits substantial control; however, for linear construction projects, channel length is a function of newly added impervious surface length. Accordingly, the loading rate will increase in proportion to channel length, making channel length potentially less influential. Side slope has a weak effect on annual volume reduction percentage. Design side slope will likely be limited by erosion more so than its role in infiltration optimization. The effect of Manning's n values on infiltration in this model is in agreement with research by Backstrom (2003) that found that vegetation density is positively associated with TSS removal efficiency. A summary of recommended design infiltration rates is presented in Table 2.3. In most cases, a minimum design infiltration rate of 0.5 in/hr is recommended in biofiltration systems where freezing and clogging are not likely.

Table 2.3 Recommended infiltration rates for stormwater BMPs in various locations.

Reference	Recommended Minimum Infiltration (in/hr)	Notes
Claytor and Schuler, 1996	0.25 in/hr	Conservative to account for clogging
EPA, 1999	0.5 in/hr	Vegetated swale
PAEPA, 2006	0.5 in/hr	Vegetated swale
Iowa Stormwater Management Manual, 2009 (Iowa DNR, 2009)	0.3 in/hr	Swales
NRCS, 2005	0.5 in/hr	Bioswales
Stenlund, 2014b	1.02 in/hr	Unless underdrain is provided
MnDOT Construction Specs, 2014a	4.0 in/hr minimum	Filter media

While the rates presented in Table 2.3 are a recommended minimum, Yousef et al. (1987) indicate that higher rates are preferable. It is also recommended to use a factor of safety of 2 to 3 with infiltration rates to account for the negative impacts of freezing, clogging, and compaction (Abida and Sabourin, 2006). In Minnesota, where freezing is common and salting and sanding of roadways increases sediment loads and potential for clogging, a minimum infiltration rate of 4 in/hr is required for filtration media topsoil (MnDOT Construction Specs, 2014a). A maximum infiltration rate of 8.3 in/hr is designated the Minnesota Construction Stormwater Permit to ensure water retention suitable for plant growth and contact time for pollutant removal. The Minnesota stormwater manual recommends infiltration rates for bioretention devices, including bioslopes and bioswales, should be between 1in/hr to 8 in/hr. These design guidelines reflect the consideration of cold weather climates and previous studies' factor of safety recommendations. The impact of cold climates on infiltration is a function of the time and rate of draining between wetting and freezing. Shorter drainage times in poorly draining soils result in an infiltration capacity of just 5% of thawed conditions. Soils that are more free-draining are able to retain an infiltration capacity of 30% of thawed conditions (Al-Houri et al., 2009). Compaction has been found to reduce infiltration capacity by 70 – 99% (Gregory et al., 2006). The detrimental effects of clogging and compaction are likely mitigated by plant root action (Deletic et al., 2009). For example, Ahmed et al. (2015) found that of six roadside swales analyzed in Minnesota and Wisconsin, the infiltration rates of the top 20 cm (7.9 in) of the surface soil layer were, on average, 2.8 times the published mean values for the soil classes identified.

Road salts, swelling clays, and organic mineralization may reduce the filtration capacity of filter media. High salt concentrations, such as those produced by road salting, in stormwater discharging to soils adjacent to roadways can reduce soil permeability (Fay and Shi, 2012; Henry, 1991; Public Sector Consultants Inc., 1993; Ramakrishna and Viraraghavan, 2005). The reduction in permeability is due to sodium ions interacting with organic and inorganic particles causing them to break up and then wash into and plug the pore spaces of underlying soil layers. The decreased permeability ultimately leads to increased runoff and pollutant transport (Public Sector Consultants Inc., 1993). Kakuturu and Clark (2015) found that clogging and the subsequent reduction in permeability is greater in stormwater filter media with compost amendments than it is without compost. Literature on the effect of high salt concentrations on the infiltration rates of peat and muck specifically was not found.

Clay content has also been found to have a negative impact on infiltration rate in soil media, especially when it is manually compacted (Sileshi et al., 2012). However, the high water holding capacity of clays results in significant swelling during wetting and shrinking during drying, which may alleviate the effects of compaction. In addition, the high water retention capacity of clays may provide enhanced compaction alleviation when subjected to freeze-thaw cycles (Jabro et al., 2012). These effects, combined with clays' ability to provide enhanced pollutant removal due to a relatively high cation exchange capacity, indicate that some clay content in biofiltration media may be beneficial.

Decomposition or mineralization of organic materials may also reduce infiltration capacity due to an increase in the fine fraction of the soil and a decrease in pore space. This effect is especially noted in peat, where the degree of decomposition can vary greatly between samples (Kellner, 2007). It is also important to note that once peat is removed from its subsurface oxygen-poor environment it may continue to decompose at a faster rate, leading to decreased infiltration rates over time (Stenlund, 2014b). Huang et al. (2009) also found that a greater degree of decomposition results in lower hydraulic conductivities in organic soils, results which are supported by basic soil mechanics. Due to this effect, it is important to know the type and degree of decomposition of any peat, compost, or other organic soil used in a stormwater infiltration device in order to predict its hydrologic behavior.

The percentage of organic material in a filter media has also been found to impact infiltration and water retention capacities (Sileshi et al., 2012). Laboratory studies by Sileshi et al. (2014) found that increasing percentages of peat resulted in increasing infiltration rates in peat-sand filters. Walczak et al. (2002) found that increasing the percentage of organic matter in a sand mixture from 0.1% to 23% resulted in a 34 – 46% increase in water retention. Increasing organic material content over 23% showed diminishing water retention returns. These findings indicate that an optimum organic content to maximize water retention exists at or around 23% depending on the material used. Faucette et al. (2007) also found that adding organic material in the form of yard-waste compost increases the water volume reduction capabilities of stormwater control devices.

2.6.2 Vegetation

Vegetation appears to play several important roles in the performance of stormwater biofilters. First, by slowing the velocity of runoff as it's conveyed across a biofilter, vegetation allows for increased settling of suspended solids and infiltration (Backstrom, 2003; Gulliver et al., 2014). Backstrom (2002) found that the highest suspended solids removal rates occurred in swales with the densest vegetation. Additionally, Barrett (2004) found that solids removal performance of buffer strips declined rapidly when vegetation coverage fell below 75 – 80%. Second, vegetation has the ability to alleviate the effects of clogging and compaction, thereby maintaining higher infiltration rates (Read et al., 2008). This alleviation is due to plant root action and can maintain or improve infiltration rates of the soil, a previously discussed and important factor to performance (Deletic et al., 2009). Despite the benefits of planting, removal of the upper layer of soil is recommended as a regular maintenance procedure (Claytor and Schueler, 1996; Gulliver, 2014). Finally, plants and the microbes supported by plant root zones have the ability to uptake heavy metals and nutrients from stormwater that would otherwise discharge in receiving waters, inducing toxicity and eutrophication (Pham et al., 2012; Read et al., 2008).

Native plants are the preferred vegetation for Minnesota roadsides due to their reduced maintenance needs (mowing and reseeding), increased roadside habitat and diversity, and their ability to reduce exotic and invasive weed infestations (Benik, 1998). Native plants are also recommended for stormwater treatment systems because of their hardiness and the wide range of ecosystem functions they provide (Shaw and Schmidt, 2003). A stormwater site seed mix (Stormwater Northeast 33-361) consisting primarily of native species adapted to northeast Minnesota is specified in the *Seeding Manual 2014 Edition* (MnDOT, 2014b).

There are limitations to plant establishment and growth in bioswales. Persistent inundation of bioswales significantly inhibits plant germination and growth, and shading by trees and shrubs negatively impacts growth (Mazer et al., 2001). Other environmental factors that can influence plant growth in bioswales include low water, sediment loads, pollutants and toxins, nutrients, salt, erosion, turbidity, invasive species, and herbivores (Shaw and Schmidt, 2003).

While plant species vary in their abilities to treat stormwater due to their wide variety of physical and physiological characteristics (Read et al., 2008), in general the addition of vegetation reduces stormwater pollutant concentrations and loading rates. Comparing the effect of vegetation and soil media on the removal of nitrogen, phosphorus, and carbon, Henderson et al. (2007) found that the vegetated biofilters outperformed non-vegetated biofilters in gravel, sand, and sandy-loam soil media. The improvements in pollutant reduction listed in Table 2.4 were attributed to the uptake by plants and microbes living in the root zone. Henderson et al. (2007) also note that microbial and plant uptake results in a long-term stabilization of nutrients with limited risk of leaching during subsequent rainfall events. In addition to the water quality benefits, vegetation also plays an important role in slope stability, as covered in the following section.

Table 2.4 Increases in pollutant removal with the establishment of vegetation on biofilters (adapted from Henderson et al., 2007).

	Percent Increase in Reduction with Addition of Vegetation		
Nutrient	**Gravel**	**Sand**	**Sandy-loam**
PO4	50	0	23
NOx	219	347	384
NH4	6	24	-1
TP	54	4	16
TN	75	67	52

2.7 SOIL AMENDMENTS AND FILTRATION MEDIA

An effective biofiltration soil media must be able to infiltrate stormwater at a high rate, support vegetative growth, provide water quality improvement, and maintain its structural integrity to prevent erosion and slope failure (Stenlund, 2014c). Where *in situ* soils do not perform these functions well, soil amendments are implemented (Washington Department of Transportation (WSDOT) *Highway Runoff Manual*, 2014). Currently recommended soil amendments for filtration media used in bioslopes and bioswales is composed of 60 – 80% clean sand and 20 – 40% organic compost by volume (MnDOT Specs 3877.2.G, 2016). These recommendations are based on experience, showing the mixture will comply with the NPDES requirement to retain the first inch of stormwater runoff. The ability of salvage materials such as peat, muck, and taconite tailings, which are locally available in northern Minnesota, to meet this requirement is unknown. Study and characterization of these materials may reveal their ability to perform as well or better than the currently recommended sand and compost mix. In addition, the beneficial reuse of these materials as filtration media in bioslopes and bioswales has the potential to reduce project cost, increase stormwater treatment performance, and reduce waste material.

2.7.1 Compost

Compost has been established as the organic material of choice for biofiltration soil amendments due to its ability to aid in the adsorption of heavy metals, improve infiltration of stormwater, support plant growth, and reduce erosion (Seelsaen et al., 2006a; Maurer, 2009; Pitt et al., 1999). Compost is either added to a filter media bed or applied as a top-layer blanket (WSDOT, 2014). Green waste compost, derived from grass clippings, brush trimmings, and plant materials was shown to have superior metal absorption capabilities when compared to several other soil amendments including peat, coir, bonemeal, and woodbark (Nwachukwu and Pulford, 2008). The high adsorption capacity of compost is attributed to its relatively high cation exchange capacity and neutral pH (Khan et al., 2009; Claytor and

Schuler, 1996). Seelsaen et al.'s (2006b) laboratory batch studies demonstrate excellent removal efficiencies of copper, zinc, and lead for stormwater treated with a compost filter (Table 2.5). A three-year field-monitoring study of a compost filter system summarized in Table 2.5 also found high removal efficiencies for several stormwater pollutants (CSF Treatment Systems Inc., 1994).

Nwachukwu and Pulford (2008) noted that these removal efficiencies are negatively affected in the presence of high salt concentrations and other metal ions due to competitive sorption. Seelsaen et al. (2006b) reported that composts with smaller particle size had a larger surface area and thus greater sorption potential; however, Faucette et al. (2007) warn that if particle size distribution specifications are not met, total soil loss, suspended solids, and turbidity will be greater. These findings suggest that there is an optimal particle size distribution for stormwater treatment purposes that balances adsorption potential and erosion control.

Table 2.5 Removal efficiencies of compost filters in lab and field experiments (adapted from Claytor and Schueler, 1996).

Pollutant	Setting	Removal Efficiency
Total Suspended Solids	Field	95%
Total Dissolved Solids	Field	(-37%)
COD	Field	67%
Total Phosphorus	Field	41%
Soluble Phosphorus	Field	(negative)
Organic Nitrogen	Field	56%
Nitrate	Field	(-34%)
Cadmium	Field	No Data
Lead	Lab	97%
Zinc	Field, Lab	88%, 88%
Copper	Lab	93%
Hydrocarbons	Field	87%
Copper	Field	67%

Infiltration capacity and volume reduction enhancements by compost amendments are reported throughout the literature. Faucette et al. (2005) compared compost blankets to "hydroseed" and silt fence systems and found that compost blankets reduced runoff volumes by five times that of the hydroseed treatment after three months and by 24% after a full year. Faucette et al. (2007) found that increasing percentages of compost in an erosion control blanket resulted in improved volume reduction and reduced runoff rates. A laboratory comparison of fourteen different erosion control practices showed that compost outperformed all other systems, with volume reductions between 29% and 94% for varying rainfall intensities (Faucette et al., 2009b). Glanville et al. (2004) also reported significantly enhanced infiltration capacity on compost-amended bioslopes. The ability of compost to improve infiltration enhances the overall performance of biofilters by providing volume reduction and increased contact with adsorptive media.

Yard waste compost soil amendments also have the ability to improve vegetative cover and reduce erosion. Faucette et al. (2006) reported that yard waste compost blankets produced 2.75 times the vegetative cover of hydroseed treatments while also controlling weed growth due to a lower mineralized nitrogen concentration in the yard waste compost compared to hydroseed or biosolid compost. Pitt et al. (1999) also found improved vegetative cover on compost-amended soils. Compost supports a healthy microbe population which improves nutrient availability to plants and soil aggregates that reduce soil erosion (Archuleta and Faucette, 2014; Rushton, 2001). Faucette et al. (2009a) found that compost blankets reduced soil erosion by 67 – 99% when compared to 14 other erosion control methods.

The performance of compost-amended soils is heavily dependent on the quality of compost utilized (Archuleta and Faucette, 2014). Soil pH, moisture content, organic matter, particle size, biological stability, and initial pollutant concentrations should all be considered when using compost for stormwater treatment. Specified properties for MnDOT Grade 2 compost used as a soil amendment with the intention of improving pollutant removal, enhancing plant growth, reducing erosion, and providing volume reduction are presented in Table 2.6.

Table 2.6 MNDOT Grade 2 Compost Requirements (MnDOT, 2014b).

Requirement	Range
Organic matter content	≥ 30%
C/N ratio	6:1 – 20:1
pH	5.5 – 8.5
Moisture content	35% – 55%
Bulk Density	700 lb per cubic yard – 1600 lb per cubic yard
Inert material*	≥ 3% at 0.15 in (4mm)
Soluble salts	≤10 mmho per cm
Germination test**	80% – 100%
Screened particle size	≤3/4 (19mm)
*Includes plastic bag shreds **Must list species used	

A potential issue associated with compost-amended soils is nutrient leaching. Evidence for nutrient leaching is mixed. Some studies report removal of nitrogen and phosphorus (Faucette et al., 2005; Glanville et al., 2004) while others note that leaching of nitrogen and phosphorus is possible (Gulliver et al., 2014; Lenth and Dugapolski, 2011; Faucette et al., 2007; CFS Inc., 1994). Excess nutrients have the potential to cause eutrophication in receiving waters, leading to suggestions by Faucette et al. (2005) that federal specifications for nutrient contents of soils used in stormwater management be developed. The *Minnesota Stormwater Manual* notes that adequately matured grass or plant feedstock compost has less potential to leach nutrients than that made from biosolids or animal manure. Gulliver et al. (2014) suggest that phosphorus removal can be enhanced through the addition of iron-based soil amendments while others have found peat to be effective for nutrient removal, topics that will be explored in the following sections on peat and taconite tailings.

Compost that has not been completely matured can be detrimental to plant growth. Maturity tests have been developed for evaluating compost to ensure its benefit to plants (University of Florida, 2011). Contaminants such as pesticides or other toxic substances can also be found in compost or other soils. Toxicity tests have been developed to determine their presence and effect on plant growth (ASTM, 2014; US Composting Council, 2015). These tests generally consist of plant bioassays using seeds of fast-growing plants such as lettuce or radish grown on the substrates to be evaluated. Plant growth characteristics such as seed germination, root elongation, and seedling vigor are compared to a control to determine the safety of these substrates.

The Solvita® measurement system developed at the Woods End Laboratories is another more rapid method to determine compost maturity (Woods End Laboratories, 2016). With this method, compost biological activity is determined by measuring carbon dioxide (CO_2) and ammonia (NH_3) emissions from a sample enclosed in a sealed container. Specially formulated gel probes placed within the container react to the concentrations of CO_2 and NH_3 gases, resulting in a color change. After a 24-hour period, the gel color is compared with a color chart or read with a digital color reader to determine concentrations of these gases. High concentrations of CO_2 and NH_3 are indicators of immature, unstable compost. The Solvita® system can also be used to determine soil CO_2 respiration, an indicator of soil health and potential productivity.

2.7.2 Peat and Muck

Peat is partially decomposed plant matter that is high in organic content and complex in chemical and physical structure. The elemental composition of peat consists primarily of carbon (50 – 60%), hydrogen (5 – 6%), oxygen (30 – 45%), and nitrogen (1 – 2%) (Kao and Lei, 2000). Peat is generally acidic in nature due to the presence of various functional groups in lignin that include alcohols, aldehydes, ketones, acids (such as humic acid and fulvic acid), phenolic hydroxides, and ethers (EPA, 1999; Gupta et al., 2009). The use of peat for treatment of stormwater has high interest due to its low cost, high availability, high water holding and infiltration capabilities, good vegetative support, ability to improve soil properties, and its ability to filter and adsorb pollutants (Biesboer and Elfering, 2004). The ability of peat to remove pollutants from solution is thoroughly documented. Farnham and Brown (1972) found significant reductions of phosphorus and organic pollutants in municipal wastewater treated with a peat and sand filter. Galli (1990) reports high removal efficiencies for typical stormwater pollutants treated with a peat-sand filter as shown in Table 2.7.

Table 2.7 Pollutant removal efficiencies of peat-sand filters (Galli, 1990).

Pollutant	Removal Efficiency (%)
Suspended Solids	90
Total Phosphorus	70
Total Nitrogen	50
BOD	90
Trace Metals	80
Bacteria	90

Numerous other studies have found peat to be effective for pollutant removal, primarily in heavy metal uptake, shown in Table 2.8 (Brown et al., 2000; Gundogan et al., 2004; Ringqvist et al., 2002; Kao and Lei, 2000). Several authors note that the ability of peat to capture heavy metals is dependent on pH with an optimal range of 3.5 – 8.5 (Pitt et al., 1997; Brown et al., 2000; Sharma and Forster, 1993; Crist et al., 1996). In general, peat can remove 50% of heavy metals at high concentration and more than 90% at low concentrations (Sharma and Forster, 1993; Crist et al., 1996; Gündoğan et al., 2004; Al-Faqih et al., 2008; Gupta et al., 2009; Izquierdo et al., 2009). The high metal-removal capability of peat is attributed to its high cation exchange capacity, buffering capacity, and high adsorptive surface area (Biesboer and Elfering, 2004). Metals are uptaken by peat through ion exchange, complexation, surface adsorption, and chemisorption (Crist et al., 1996; Brown et al., 2000; Gündoğan et al., 2004). The surface functional groups of peat such as aromatic carboxylates-COOH and phenolic-OH will react with metals through displacement of proton into water, as shown in Figure 2.5.

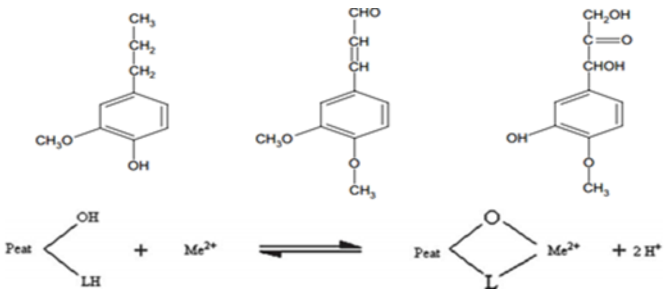


Figure 2.5 Binding mechanism of peat with metal ions (Gupta et al. 2009).

Table 2.8 Summary of peat application on removal of metals, nutrients and organic matter in stormwater runoff.

Chemicals	Lab/field	Pollutant removal efficiencies	Filter material	Inflow	Reference
Cu, Ni	Lab	Maximum adsorption capacity 17.6mg/g and 14.5 mg/L for Cu and Ni respectively	Peat moss	Lab synthesized water	Gupta et al., 2009
Organic chemicals	Pilot plant	50 – 80% for BPA, 35% for PHCs, 63% for PAHs	Peat moss	Landfill leachate	Kalmykova et al., 2014
Cu	Lab	22, 36.4, 43.7 mg/L for pH values of 4, 5, and 6, respectively	Mineralized peat	Lab synthesized water	Izquierdo et al., 2009
Cd, Cu, Ni, Zn	Lab	Zn=28%, Cd=27%, Ni=24%, Cu=21%	Peat-based sorbent	Lab synthesized water	Al-Faqih et al., 2008
Mg, Mn, Ca, Ni, Zn, Cd, Cu, Pb	Lab	At high concentration, uptake around 50% of Cd and Zn; at low concentration, remove 90% of Cd and Zn	Peat moss	Lab synthesized water	Crist et al., 1996
Cu	Lab	Remove over 90% of Cu	Herbaceous peat		Gündoğan et al., 2004
Cr	Lab	Highly dependent on pH, up to 100% removal at pH below 2.0	Peat moss	Lab synthesized water	Sharma and Forster,1993
N, P, BOD	Field & lab	Very efficient removal of P and BOD in low concentration and high temperature, around 50% removal efficiency during winter. Higher removal efficiency in presence of vegetation and aerobic condition	Peat moss, reed-sedge	Wastewater from municipal sewage treatment plant	Farnham and Brown, 1972

Nitrogen and phosphorus are the primary nutrients in storm-water runoff, originating from atmospheric deposition, roadside fertilizer application, and transported solids (Haering et al., 2006). Dissolved nitrogen is generally present in the forms of NO_3^-, NO_2^-, NH_4^+, NH_3 and organic nitrogen. The high solubility of nitrogen chemicals results in low adsorption rates in peat. However, a vegetated filtration system may improve nitrogen removal by plant uptake processes.

Peat is very efficient in removing highly concentrated phosphorus such as is typically present in wastewater and agricultural runoff. The removal efficiency could be as high as 99% at low inflow rates and under aerobic conditions. Phosphorus concentrations in effluents could be as low as 0.01 mg/L under these circumstances (Farnham and Brown, 1972). Peat filtering system removes phosphorus probably by a combination of microbial assimilation, inorganic and organic retention, and adsorption processes (Farnham and Brown, 1972). The high carbon-to-phosphorus ratio (approximately 500 – 700:1) can provide sufficient carbon sources for microbial organisms to convert inorganic phosphorus into organic phosphate complexes. Vegetation can further improve the immobilization of phosphorus by plant uptake. However, stormwater usually has low concentrations of phosphorus, generally ranging from 0.1 to 0.4 mg/L (Kayhanian et al., 2012). A mixture of peat with other iron or aluminum-rich materials will likely improve the removal efficiency since phosphorus can be strongly adsorbed on aluminum and ferric hydroxides and/or precipitate with calcium (LeFevre et al., 2014).

The application of peat for removing stormwater organic matters was not found, possibly due to the low concentrations of organic chemicals in stormwater. Peat can remove phenol, PHCs, and PAHs from landfill leachate at the removal efficiencies of 50 – 80%, 35%, and 63%, respectively (Kalmykova et al., 2014). However, landfill leachate usually has higher concentrations than stormwater. This removal efficiency may be much lower in stormwater treatment.

The hydraulic properties of peat can be highly variably depending on the degree of decomposition (Grover and Baldock, 2013). Nichols and Boelter (1982) report hydraulic conductivities ranging from 6.94×10^{-5} cm/sec to 3.89×10^{-2} cm/sec. In general, greater decomposition correlates to lower hydraulic conductivity (Pitt et al., 1997). Since peat continues to decompose after harvest and application, changing conductivity presents a potential issue for long-term performance of peat-amended bioinfiltration BMPs (Stenlund, 2014b). Therefore, more frequent maintenance or replacement of filtration materials may be required. It is also important to note that peats of different botanical origin decompose at different rates. Sphagnum peat decomposes three times faster than sedge peat when exposed to oxygen (Raviv et al., 1986). Plant derivation, moisture content, and compaction also affect peat's hydraulic conductivity (Clark and Pitt, 1999). The impact of these factors means that peat's physical and chemical structure, compaction, and decomposition status are important to its performance as a stormwater filtration media.

Plant establishment and growth is important for nutrient uptake and erosion control (Nichols and Boelter, 1982; Johnson, 2000). Peat helps retain soil moisture, reduce bulk density, and improve microbial health, all of which aid in plant growth (Biesboer and Elfering, 2004; Pitt et al., 1997). Sloan et al. (2008) demonstrated that adding peat to sand significantly improved vegetative growth in a laboratory environment.

The pollutant-removal capabilities, water-absorbing capacity, and soil-improving properties of peat make it a useful soil amendment for stormwater treatment filter media. In northern Minnesota, peat moss is often discarded as a waste product during road construction, making it readily available and affordable.

Muck is differentiated from peat, primarily by its degree of decomposition. Muck is a highly decomposed organic soil that is often excavated from construction sites due to its lack of structural integrity and low hydraulic conductivity (MnDOT, 2013). Since muck has limited use as a construction material, it is readily available at low cost. Research on muck for use as a soil amendment in stormwater treatment filtration media is limited, but due to its high organic content it may aid in the establishment of vegetation in sandy, inorganic soils. Sileshi (2013) also notes that the organic materials often have high cation exchange capacities that may improve the adsorption potential of a filter media.

2.7.3 Taconite tailings

The use of taconite tailings as an alternative stormwater filtration media offers several potential advantages including availability, favorable geotechnical properties, and enhanced phosphorus removal. Taconite tailings are readily available in northern Minnesota as an iron ore mining byproduct. MnDOT Materials Lab Supplemental Specifications for Construction (2016) requires that taconite tailings used for MnDOT projects be obtained from mines located westerly of a north-south line located east of Biwabik, Minnesota (R15W – R16W). Samples collected for this project will be obtained from mining operations that meet MnDOT requirements. It is estimated that the production of one ton of taconite pellets generates nearly an equal amount of course tailings, much of which are considered waste product (Zanko et al., 2003). The beneficial reuse of these tailings for stormwater filter media may offer a mutually beneficial solution to stormwater managers and the mining industry.

The advantageous physical properties of taconite tailings include high strength and the ability to improve hydraulic conductivity when added to other soils (Lund, 2014; Zanko et al., 2003). These properties will improve the stability and infiltration capacities of soils used in bioslopes and bioswales. In addition to the favorable physical properties, the iron content of taconite tailings may improve the ability of stormwater filters to remove phosphorus. Erickson et al. (2007, 2010, 2012) demonstrated a significant increase in the removal of dissolved phosphorus from stormwater is possible when filters are amended with iron. Field application studies of iron-enhanced sand filtration trenches showed an 85 – 90% reduction in phosphorus loads to stormwater ponds (Erickson et al., 2012). Moreover, heavy metals may bind to hydroxide iron and precipitate onto sorbent surface, consequently improving the removal of heavy metals from stormwater (Smith and Falls, 2001; Wu and Zhou, 2009).

Though taconite tailings are not typically conducive to plant growth due to low nutrient content and lack of moisture retention, amendments with organic materials have shown that substantial vegetation growth is possible (Norland and Veith, 1995). Felleson (1999) found that as little as 10 to 22.4 metric tons/ha of organic material applied to bare, coarse taconite tailings was sufficient for establishing vegetative cover. Potential issues associated with taconite tailings include increased transportation costs due to high bulk density (Zanko, 2007).

2.8 OPTIMIZING GEOTECHNICAL PROPERTIES OF FILTRATION MEDIA SOILS

Effective bioslopes and bioswales must improve water quality, support plant growth, and maintain the physical properties necessary to prevent erosion. In many ways, the ability of these BMPs to meet performance requirements are dependent on the geotechnical properties of the soil employed as a filtration media. Important parameters include hydraulic conductivity, response to compaction, and strength (Sileshi, 2013).

The hydraulic conductivity and response to compaction can be optimized in a filtration media by maximizing the content of sand or other coarse-grained inorganics such as taconite tailings. Sileshi (2013) found that the negative impact on infiltration associated with compaction of soils was mitigated by increasing sand content in biofilter media. It was also found that the infiltration capacity of soils with high organic content and, in particular, peat was negatively affected by compaction. As previously discussed, the infiltration rate of filter media has a strong effect on performance and, therefore, the response to compaction of alternative filter media should be thoroughly characterized. Understanding the response to compaction will help optimize a filtration media mix design and help guide placement and maintenance procedures.

Soil strength is important for slope stability. Strength can be optimized by maximizing permeability, particle angularity, gradation, and compaction while minimizing organic content (Coduto et al., 2013). While slope stability should be considered in the design and construction of bioslopes and bioswales, the performance of these BMPs is negatively affected by soil compaction (Sileshi, 2013). In addition, a lack of organic content reduces vegetative support and promotes erosion (Faucette et al., 2007). Ultimately, a useful bioinfiltration media mix design will have to balance strength requirements with growth support and erosion control requirements.

2.9 CONCLUSION

Bioslopes and bioswales are effective stormwater management BMPs suitable for meeting NPDES requirements that require the capture of the first inch of runoff from highway construction projects. The efficiency of bioslopes and bioswales to capture runoff and improve water quality is dependent on several factors, including filter media characteristics. Infiltration capacity, resistance to compaction, ability to support vegetation, erosion resistance, pollutant adsorption capacity, pH, and chemical composition are key to the performance of filter media used in bioinfiltration devices. These parameters can be optimized in alternative filter media through proper mix design to satisfy the biological, environmental, hydrological, and geotechnical performance goals of bioslopes and bioswales.

CHAPTER 3: MATERIALS

3.1 INTRODUCTION

A number of treatment media sources for use in the research project were identified in MnDOT District 1 or close proximity. The potential materials include compost, salvaged peat, muck, commercial peat, sand, and taconite tailings. Samples of sufficient volume for characterization and performance trials were collected in five-gallon pails in October and November 2015 (Table 3.1). Compost and taconite tailings samples were collected from recently stockpiled (2015) materials. Salvaged peat and muck were collected from stockpiles established during the Highway 53 reconstruction (2013). These stockpiles were covered with varying amounts of vegetation that had to be removed prior to sample collection. Commercial peat was donated by Premier Horticulture and was received in 3.8-cubic-foot compressed bales. Sand samples came from Arrowhead Concrete Works Inc. MnDOT Sand Pit 69511 in Solway Township, Minnesota.

Table 3.1 Summary of filtration materials and their locations, collection date and methods.

Filtration material	Location	Collection date	Collection method	Weather on collection date
Compost	WLSSD waste facility	Oct. 30, 2015	Shovel	Had relatively heavy rain the day before, cloudy on sample collection day
Peat	1944 Hwy 53, Cook, MN	Nov. 5, 2015	Shovel	Had light rain the day before, and rain on the morning of sampling day
Muck		Nov. 5, 2015	Shovel	
Taconite tailing	ArcelorMittal, Gilbert, MN	Nov. 5, 2015	Shovel	
Commercial peat	Premier Horticulture, Cromwell, MN	Summer 2015	Vacuum harvester	Unknown
Sand	Solway Township, MN	Fall 2015	Bulk sample received	N/A

3.2 SAMPLE COLLECTION

3.2.1 Compost

Compost was purchased from the Western Lake Superior Sanitary District (WLSSD) yard waste management site located on Courtland Street off Interstate 35 at 27th Avenue West and the waterfront in Duluth, Minnesota (Figure 3.1). Compost was collected on October 30, 2015 (Figure 3.2). There was a light rain on October 27 (0.13 in), heavy rain on October 28 (0.62 in) and light rain on October 29 (0.10 in) (NOAA, 2017). However, the compost was stockpiled, so the materials within the pile were relatively dry.

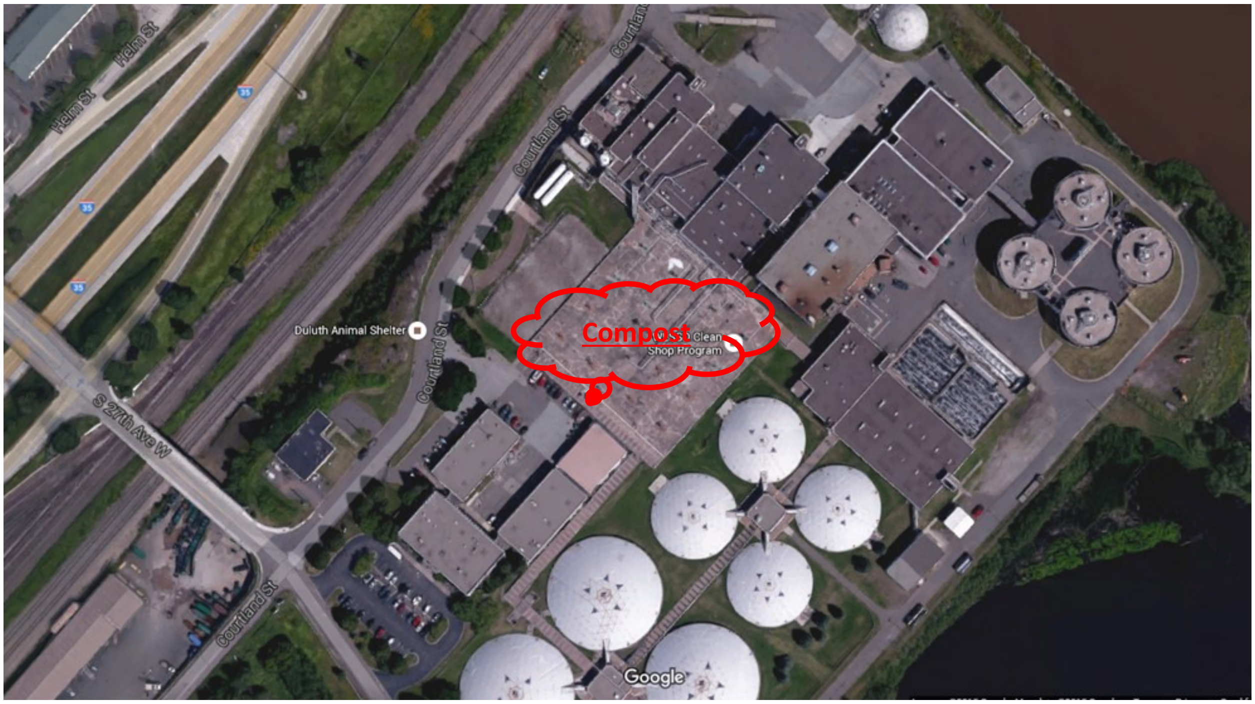


Figure 3.1 Overhead view of the WLSSD compost site located at the waterfront and 27th Ave W in Duluth, MN.

Figure 3.2 Compost pile (left) in WLSSD and a close-up view of the compost samples (right).

The WLSSD compost originated from grass clippings, leaves, garden debris, brush, fresh-cut holiday trees, and small quantities of sod and dirt (WLSSD, 2015). WLSSD compost has been monitored and certified by the US Composting Council (Table 3.2). The samples collected were from piles that had fully completed the composting process and were considered "mature."

Table 3.2 Characteristics of compost samples by US Composting Council (WLSSD, 2015).

Compost Parameters	Reported as (units of measure)	Test Results	Test Results
Plant Nutrients:	%, weight basis	Not reported	Not reported
Moisture Content	%, wet weight basis	44.3	
Organic Matter Content	%, dry weight basis	62.2	
pH	units	6.44	
Soluble Salts *(electrical conductivity)*	ds/m (mmhos/cm)	11	
Particle Size or Sieve Size	maximum aggregate size, inches	0.64	
Stability Indicator (*respirometry*)			Stability Rating:
CO_2 Evolution	mg CO_2-C/g OM/day	9.1	Un-Stable
	mg CO_2-C/g TS/day	5.7	
Maturity Indicator (bioassay)			
Percent Emergence	average % of control	100	
Relative Seedling Vigor	average % of control	81.7	
Select Pathogens	PASS/FAIL: per US EPA Class A standard, 40 CFR § 503.32(a)	Pass	*Fecal coliform*
		Pass	*Salmonella*
Trace Metals	PASS/FAIL: per US EPA Class A standard, 40 CFR § 503.3, Tables 1 and 3	Pass	*As, Cd, Cr, Cu, Pb, Hg*
			Mo, Ni, Se, Zn

3.2.2 Peat and muck

The peat and muck samples were collected from the "Tini Pit" north of Cook (1944 Highway 53, Cook, MN) on November 5, 2015 (Figure 3.3). The peat and muck were deposited there in January-February 2013. They originally came from the Highway 53 road reconstruction project in the two-mile stretch just south of Cook. There was light rain on November 1 (0.07 in) and November 2 (0.06 in). It was dry on November 3 and 4, with light rain in the morning on November 5 (0.05 in). The project team had previously visited this site during the kick-off meeting on June 1, 2015. At that time, it was noted that the muck area had little to no vegetation but rich vegetation in the peat area (Figures 3.4 and 3.5). On the November sampling date, some plants were observed on the muck area, although it was still sparsely vegetated compared to the peat area. Surface vegetation was removed prior to sample collection.

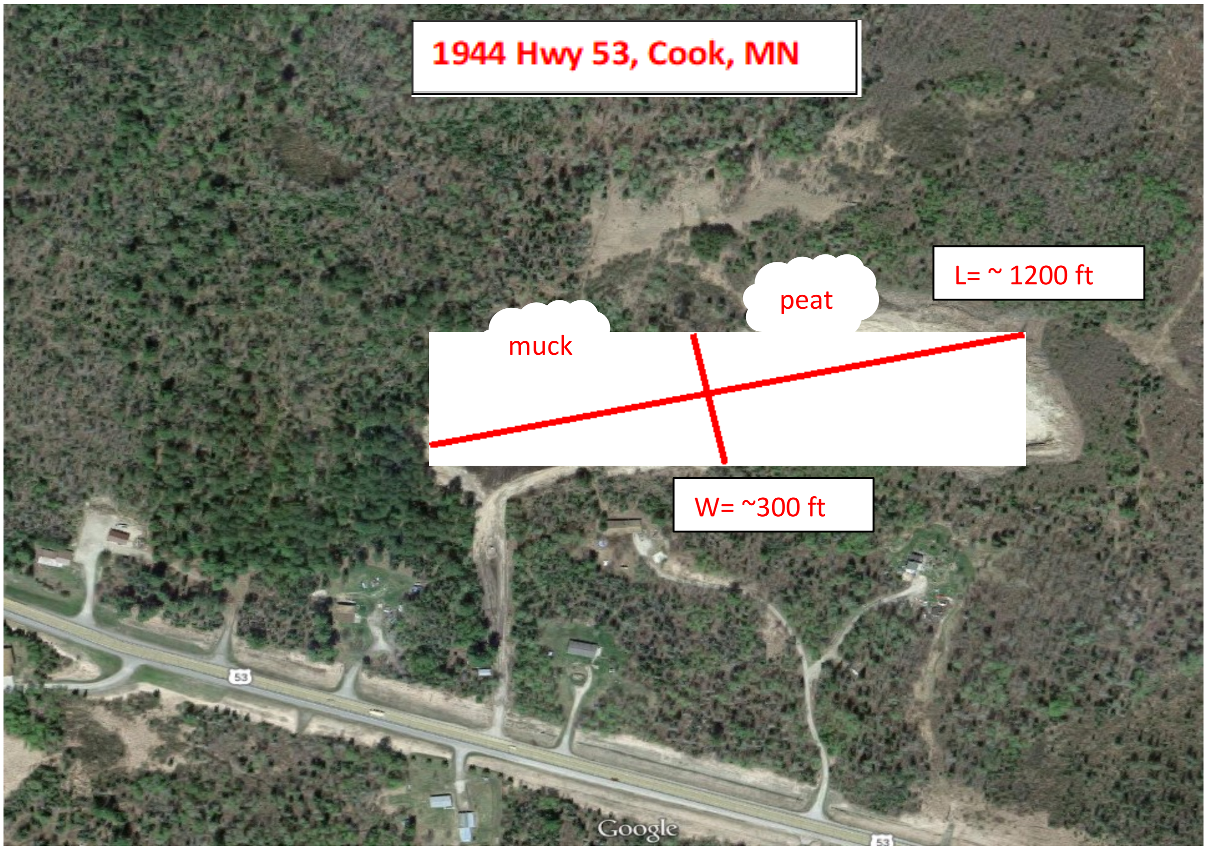


Figure 3.3 Overhead view of the "Tini Pit" peat and muck sampling location north of Cook, MN.

Figure 3.4 Summer (left) and fall (right) view of the peat and muck sites. The muck area did not have any vegetation in the summer and minimal vegetation in the fall. The peat area had dense vegetation cover throughout the growing season.

Figure 3.5 Close-up view of muck (left) and peat (right) samples.

3.2.3 Taconite tailings

Taconite tailings are an iron ore processing by-product that is of a consistent grain size distribution. Tailings samples were collected from a site near Gilbert on November 5, 2015 (Figures 3.6 and 3.7), the same date as the peat and muck collection. For a previous project (Zanko et al., 2010), eight grab samples were collected from this location for grain size analysis and submitted to Precision Testing, Inc. in Virginia, Minnesota (Table 3.3).

Figure 3.6 Overhead view of the ArcelorMittal Minorca mine near Gilbert, MN. This is the origin of the taconite tailings, although samples were collected from a smaller stockpile off-site.

Figure 3.7 Taconite tailing pile (left) and close view (right).

Table 3.3 Taconite tailing gradation (Zanko et al., 2010).

Product 4	-4 (-4.75mm) screened taconite fine aggregate (coarse tailings0
Date Produced	Apr-09
Source	ArcelorMittal Minorca Mine
Pile Location	Ulland Brothers ArcelorMittal Minorca – Gilbert site
Tons	2,500 (approx.)
Gradations run	8

Gradation U.S. Sieve	Maximum % passing	Minimum % passing	Average % passing		Sieve interval	Average per interval	Interval Min	Interval Max
4	100.0	100.0	1000		+4	0.0	0	0
8	90.0	87.1	88.6		4 x 8	11.4	10	13
16	67.0	64.3	65.7		8 x 16	22.9	20	26
30	44.0	42.5	43.3		16 x 30	22.4	20	25
50	22.3	21.6	22.0		30 x 50	21.3	20	23
100	8.6	8.1	8.3		50 x 100	13.8	13	15
200	4.4	4.0	4.2		100 x 200	4.1	3	5
					-200	4.2	0	5

3.2.4 Commercial peat

Horticultural Sphagnum moss peat was donated by Premier Horticulture, Inc. located west of Cromwell, Minnesota. The peat is field dried and vacuum harvested on Premier's Black Lake Bog (Figure 3.8), then screened, compressed, and packaged into 3.8-cubic-foot bales at their packaging plant. The peat received was harvested during the 2015 field season. Premier's company specifications for a similar peat are shown in Figure 3.9.

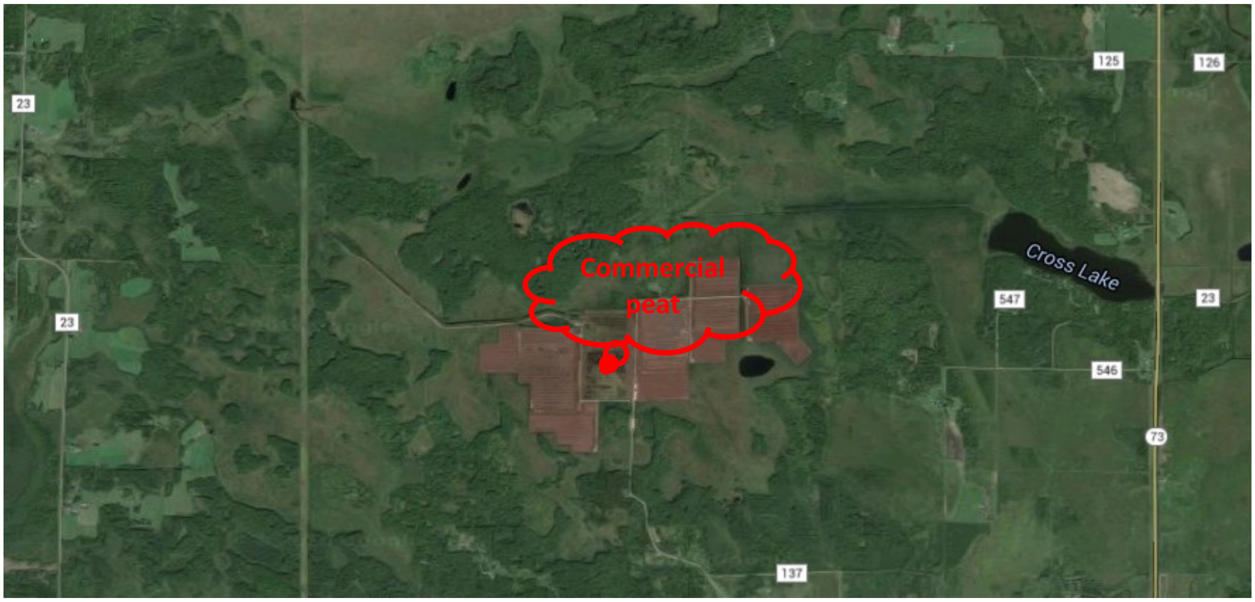
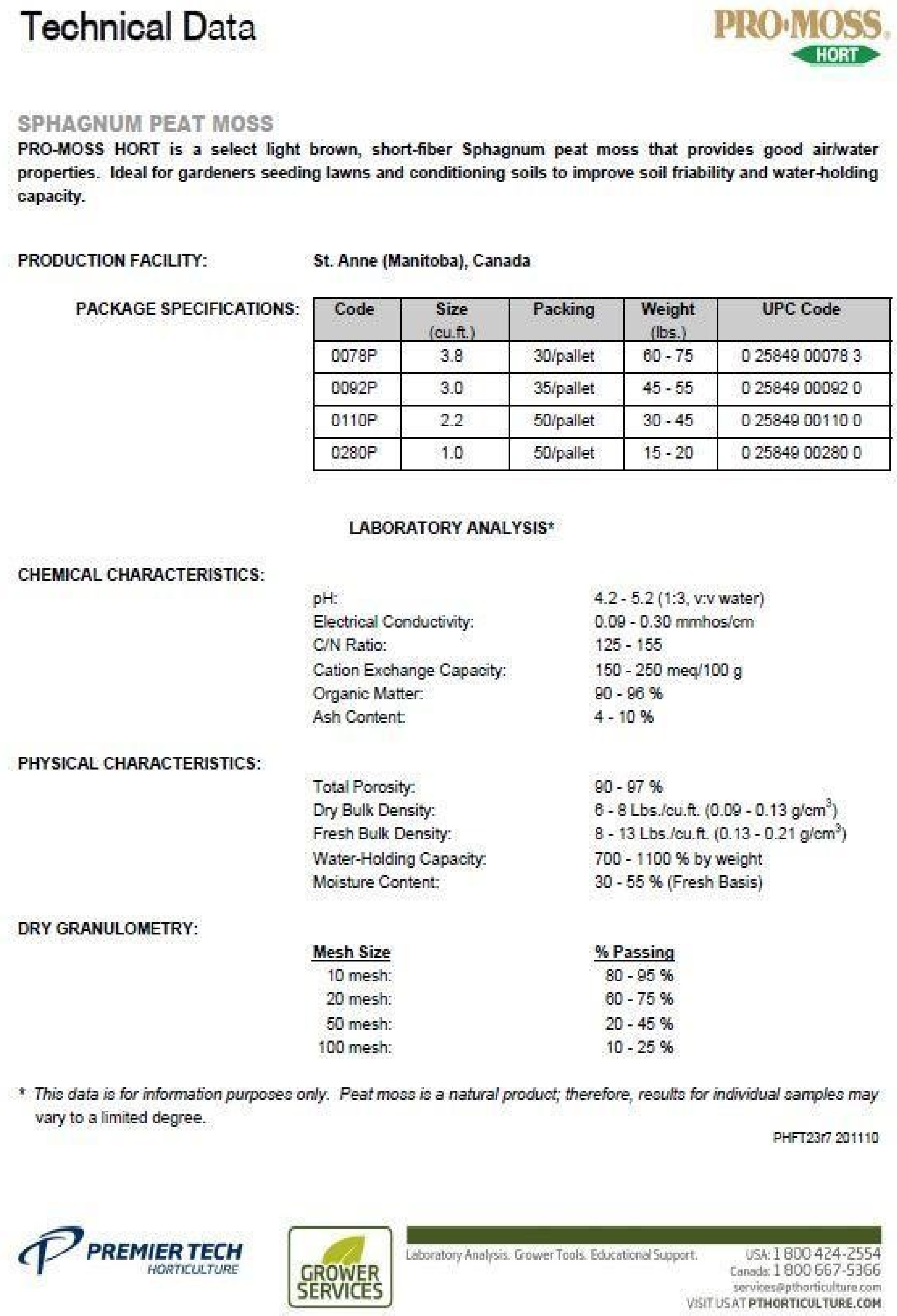


Figure 3.8 Overhead view of the Premier Black Lake horticultural peat operation where the commercial peat samples originated.



Technical Data

PRO·MOSS HORT

SPHAGNUM PEAT MOSS

PRO-MOSS HORT is a select light brown, short-fiber Sphagnum peat moss that provides good air/water properties. Ideal for gardeners seeding lawns and conditioning soils to improve soil friability and water-holding capacity.

PRODUCTION FACILITY: St. Anne (Manitoba), Canada

PACKAGE SPECIFICATIONS:

Code	Size (cu.ft.)	Packing	Weight (lbs.)	UPC Code
0078P	3.8	30/pallet	60 - 75	0 25849 00078 3
0092P	3.0	35/pallet	45 - 55	0 25849 00092 0
0110P	2.2	50/pallet	30 - 45	0 25849 00110 0
0280P	1.0	50/pallet	15 - 20	0 25849 00280 0

LABORATORY ANALYSIS*

CHEMICAL CHARACTERISTICS:

pH:	4.2 - 5.2 (1:3, v:v water)
Electrical Conductivity:	0.09 - 0.30 mmhos/cm
C/N Ratio:	125 - 155
Cation Exchange Capacity:	150 - 250 meq/100 g
Organic Matter:	90 - 96 %
Ash Content:	4 - 10 %

PHYSICAL CHARACTERISTICS:

Total Porosity:	90 - 97 %
Dry Bulk Density:	6 - 8 Lbs./cu.ft. (0.09 - 0.13 g/cm^3)
Fresh Bulk Density:	8 - 13 Lbs./cu.ft. (0.13 - 0.21 g/cm^3)
Water-Holding Capacity:	700 - 1100 % by weight
Moisture Content:	30 - 55 % (Fresh Basis)

DRY GRANULOMETRY:

Mesh Size	% Passing
10 mesh:	80 - 95 %
20 mesh:	60 - 75 %
50 mesh:	20 - 45 %
100 mesh:	10 - 25 %

* *This data is for information purposes only. Peat moss is a natural product; therefore, results for individual samples may vary to a limited degree.*

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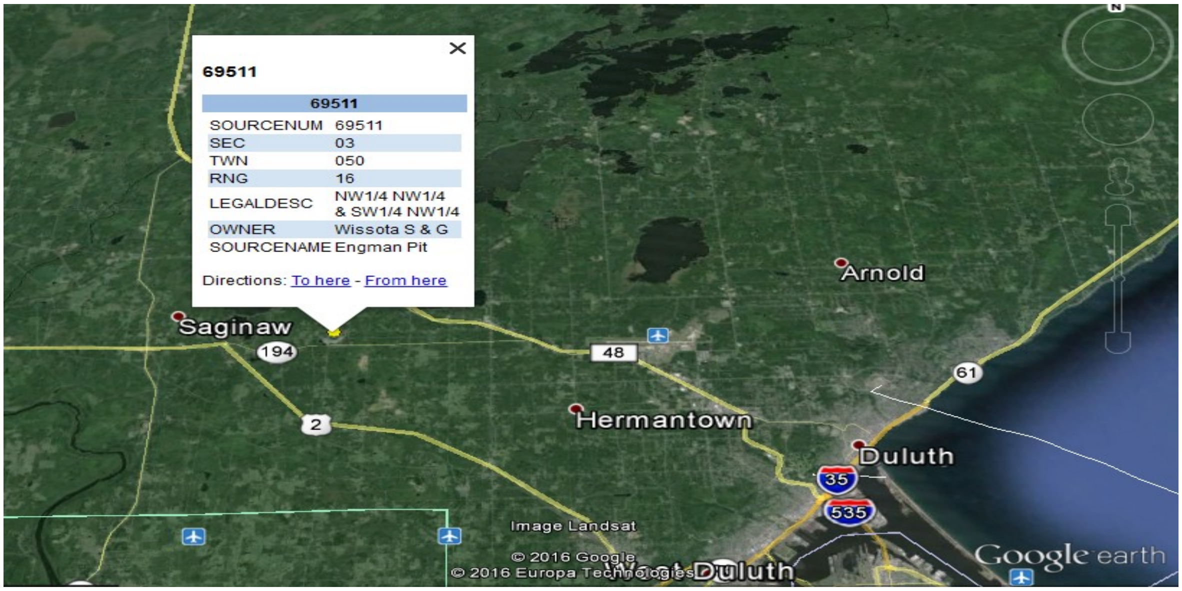
Figure 3.9 Premier Horticulture Sphagnum peat specifications.

3.2.5 Sand

Screened sand was purchased from Arrowhead Concrete Works Inc. for use in the filter media mixtures. Arrowhead Concrete Works is a distributor of sand sourced from MnDOT Pit number 69511 located in Solway Township near Saginaw, Minnesota (Figure 3.10). Sand gradation is provided in Figure 3.11 and Table 3.4.



69511

69511	
SOURCENUM	69511
SEC	03
TWN	050
RNG	16
LEGALDESC	NW1/4 NW1/4 & SW1/4 NW1/4
OWNER	Wissota S & G
SOURCENAME	Engman Pit

Directions: To here - From here

Figure 3.10 Map of sand source, MnDOT pit number 69511.

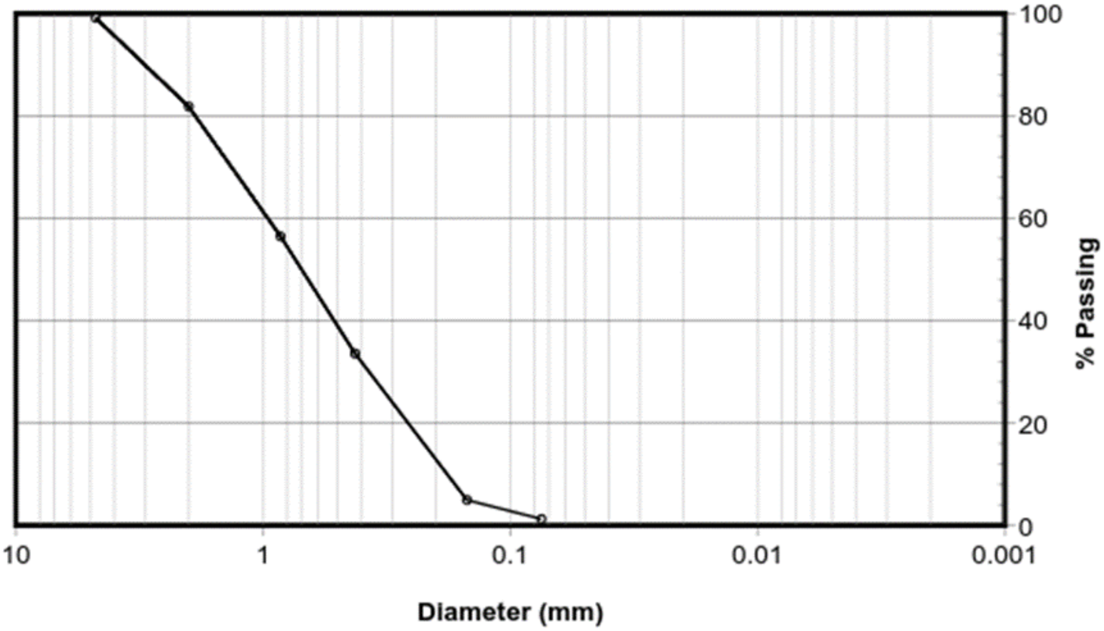


Figure 3.11 Gradation curve for Solway Township Sand.

Table 3.4 Tabulated grain size distribution for Solway Township sand.

Sieve No.	Sieve Opening (mm)	% Retained	% Passing
4	4.75	0.9	99.1
10	2.000	18.2	81.8
20	0.850	43.5	56.5
40	0.425	66.4	33.6
100	0.150	95.1	5.0
200	0.075	98.7	1.3

CHAPTER 4: METHODS

4.1 INTRODUCTION

This chapter provides a description of tests and procedures used to classify and characterize materials used as filter media for stormwater bioinfiltration devices. Materials studied include: commercial compost, commercial peat, salvaged peat, muck, sand, and taconite tailings. Tests were selected based on a review of the literature which identified important physical, chemical and biological properties. There are four main objectives of the tests: (1) to classify the study materials for aiding in the reproducibility of the study results; (2) to define the properties of the individual study media in order to predict their performance when applied in-situ; and (3) to inform the development of filter media mix designs that optimize the stormwater treatment performance in bioinfiltration BMPs. The performance of the new filter media mixtures was compared to existing compost based media mixtures as defined by the 2016 MnDOT General Construction Specifications Section 3877.2(G) “Filter Topsoil Borrow” and outlined in the section below.

4.1.1 Current Filter Media Specifications

MnDOT specifications (2016) for filter media topsoil call for a mixture of 60% – 80% sand meeting gradation requirements found in section 3126, “Fine Aggregate for Portland Cement Concrete” (Table 4.1) and 20% – 40% Grade 2 compost as defined by specification 3890 (Table 4.2). This sand-compost mixture is designed to support plant growth, provide water quality enhancement, and filtration at a rate of “at least 4 in/h.” New filter media mixtures were designed and assessed using this specification as a reference point. In addition to the requirements in Table 4.2, Grade 2 compost must also be “humus-rich, derived from the decomposition of leaves and yard wastes, and have a texture similar to shredded peat” (MnDOT, 2016).

Table 4.1 Gradation requirements for fine aggregate (MnDOT, 2016).

Sieve Size	Percent Passing*
⅜ in [9.50 mm]	100
No. 4 [4.75 mm]	95 – 100
No. 8 [2.36 mm]	80 – 100
No. 16 [1.18 mm]	55 – 85
No. 30 [600 µm]	30 – 60
No. 50 [300 µm]	5 – 30
No. 100 [150 µm]	0 – 10
No. 200 [75 µm]	0 – 2.5
* Percent passing by weight through square opening sieves.	

Table 4.2 Summary of Grade 2 compost requirements (MnDOT, 2016).

Requirement	Range
Organic matter content	≥ 30 %
C/N ratio	6:1 – 20:1
pH	5.5 – 8.5
Moisture content	35% – 55%
Bulk density	700 lb per cu. yd – 1600 lb per cu. yd [415 kg per cu. m – 890 kg per cu. M]
Inert material*	< 3% at 0.15 in [4 mm]
Soluble salts	≤ 10 mmho per cm
Germination test**	80% – 100%
Screened particle size	≤ ¾ in [19 mm]
* Includes plastic bag shreds. ** Germination test must list the species of Cress or lettuce seed used.	

4.2 INDIVIDUAL TREATMENT MEDIA CHARACTERIZATION

4.2.1 Civil Engineering

Individual treatment media was characterized in order to form filter media mix designs and provide comparative analyses to currently specified filter media (i.e., sand and compost). Knowledge of individual filter media is also necessary for the meaningful analysis of filter media mix performance with regard to its constituents. The civil engineering faction of this research team focused on relevant geotechnical and hydrological engineering properties such as: particle size distribution, soil moisture content, hydraulic conductivity, infiltration capacity and strength. The following sections describe the testing protocols for determining the geotechnical and hydrological properties.

4.2.1.1 Classification

Soil classification was conducted in order to aid in the identification of similar materials for use in the field or reproducibility in future laboratory tests. Taconite tailings, sand, and muck were classified according to ASTM D2487-11 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System; ASTM, 2011a). For the proper classification of muck, ASTM D2487-11 requires the determination of the Atterberg limits. Atterberg limits were determined according to ASTM D4318 “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils” (ASTM, 2010b).

MnDOT specifications for Grade 2 compost ensure proper identification, eliminating the need for further classification. Commercial compost from a MnDOT-certified distributor was tested by the U.S. Composting Council (Laboratory Number: 5050829-1/1) to ensure that properties are in compliance with a MnDOT Grade 2 compost classification. Non-compliance of any parameter will be reported. Peat will be categorized according to ASTM D4427-13, “Standard Classification of Peat Samples by Laboratory

Testing" (ASTM, 2013). ASTM D4427 requires the completion of several additional tests as summarized in Table 4.3.

Table 4.3 Summary of tests required for classification of peat (ASTM, 2013).

Parameter	Standard
Fiber Content	ASTM D1997-13 Standard Test Method for Laboratory Determination of the Fiber Content of Peat Samples by Dry Mass
Ash Content, pH	ASTM D2974-14 Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils
Absorbency	ASTM D2980-04 (2010) Standard Test Method for Volume Mass, Moisture-Holding Capacity, and Porosity of Saturated Peat Materials

4.2.1.2 Particle Size Distribution

Determination of the particle size distribution of all materials except peat was conducted according to ASTM D422-63 Standard Test Method for Particle-Size Analysis of Soils (ASTM, 2007). For peat, ASTM D2977-14 Standard Practice for Particle Size Range of Peat Materials for Horticultural Purposes was used. Particle size distribution is used both for soil classification and for MnDOT specification compliance.

4.2.1.3 Moisture Content

Moisture content of the study materials was determined according to ASTM D2216-10 "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass" (ASTM, 2010a). A sample of the prepared media will be taken during testing for moisture content verification by ASTM D2216-10.

4.2.1.4 Hydraulic Conductivity

The saturated hydraulic conductivity of a soil is approximately equal to its long-term infiltration rate when subjected to high rainfall or runoff rates (Figure 4.1). It follows that the *Minnesota Stormwater Manual* recommends using field saturated hydraulic conductivity as the design infiltration rate for bioretention devices. The *Minnesota Stormwater Manual* also notes that air entrapment in soils under field conditions makes totally saturated flow unlikely thereby reducing infiltration rate. Due to this condition, laboratory tests for saturated hydraulic conductivity, which eliminate entrapped air, will likely result in a higher saturated hydraulic conductivity than what is expected for an *in-situ* saturated hydraulic conductivity. With consideration for this deviation from the field conditions, an accurate comparative analysis of the filter media is possible using laboratory saturated hydraulic conductivity testing.

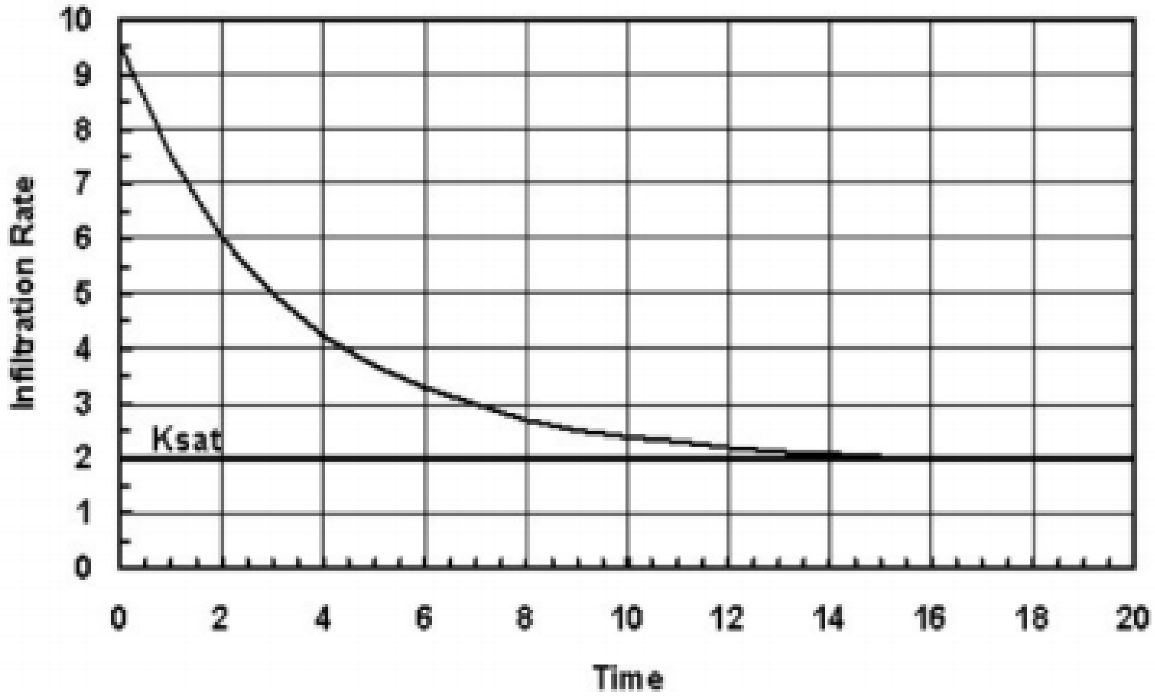


Figure 4.1 Relationship between infiltration rate and saturated hydraulic conductivity (Jarrett, 2014).

For the purposes of preliminary mixed media design and comparative analysis, the saturated hydraulic conductivity was used as a proxy for *in situ* infiltration rates. This allows for the use of well-established procedures and reproducible results. Results obtained from these tests can be used as a reference point for infiltration tests conducted in later stages of this project. In addition, a correlation of laboratory-measured saturated hydraulic conductivity to *in-situ* performance is possible, if field data becomes available. To determine the saturated hydraulic conductivity, a falling or constant head test was performed depending on the soil particle size. Testing procedures for sand, taconite tailings, compost, and muck followed those outlined by Germaine and Germaine (2009). For peat, ASTM D4511-11, “Standard Test Method for Hydraulic Conductivity of Essentially Saturated Peat,” was used (ASTM, 2011b).

4.2.1.5 Strength Testing

Soil strength testing was performed to provide comparative insight on the strength and stability of study materials as compared to sand and compost. Direct shear testing was conducted in accordance with ASTM D3080-04, “Direct Shear Test of Soils Under Consolidated Drained Conditions,” in order to determine the effective internal friction angle (ϕ’) and cohesion (c’).

4.2.2 Environmental Engineering

Environmental experiments tested chemical properties and pollutant removal efficiency of individual filter media by laboratory batch and column leaching experiments. The parameters to be examined include pH, nutrient content (nitrogen, phosphorus), and heavy metal concentrations (copper, iron, lead, zinc). The soluble chemicals were extracted by deionized (DI) water to test chemical contents of filtration materials. To test the pollutant removal efficiency at steady condition, laboratory synthetic solutions were prepared to simulate stormwater runoff. The concentrations of chemicals in synthetic solutions are designed to match the major range of stormwater chemicals in Minnesota State and the national stormwater based on data from National Stormwater Quality Database (Pitt and Maestre, 2015). The stormwater pollutants to be examined are nutrients (nitrogen and phosphorus) and heavy metals (copper, lead, and zinc).

4.2.2.1 Synthetic Runoff Preparation

The synthesized solution was prepared by dissolving $NaNO_3$, $NaH_2PO_4 \cdot H_2O$, $CuCl_2 \cdot 2H_2O$, $Pb(NO_3)_2$ and $Zn(NO_3)_2 \cdot 6H_2O$ into deionized water to gain pollutant concentrations at five different levels (Table 4.4).

Table 4.4 Chemical concentrations of solutions prepared for batch experiment.

Solution ID	Concentration level	NO_3, mg/L	PO_4, mg/L	Cu, µg/L	Pb, µg/L	Zn, µg/L
Deionized water	L1*	0	0	0	0	0
S001	L2**	7.70	5.71	1080	688	1182
S002	L2	7.74	5.12	857	479	1102
S003	L2	9.50	6.06	708	813	1094
S004	L3	15.91	12.22	1844	1001	5274
S005	L3	15.31	12.67	1552	1251	5136
S006	L4***	20.60	24.85	2961	2564	9991
S007	L5***	71.11	50.98	7076	5503	22597

*DI water, to test soluble chemical properties of filter media
**Minnesota maximum concentrations
***National maximum concentrations

4.2.2.2 Batch Experiments

Batch experiments were performed in 250 ml bottles by mixing 250 ml laboratory-synthesized solution and 2.5 g filtration material which was dried at 105 °C for 24 hours immediately before use. The mixture was shaken at 100 rpm for 24 hours (Figure 4.2) and vacuum filtered through 0.45 µm membrane. The supernatant was stored in 4 °C cooling room for nitrate and phosphate measurement by ionic chromatography (IC) or acidified by concentrated nitrate (trace metal grade) for metal measurement by Atomic Absorption Spectrometry (AAS).

Figure 4.2. Mixture of synthesized stormwater and filtration materials was being shaken at 100 rpm.

For each solution and filtration material mixture, three replicates were run at same time. Due to the space limit of the shaker, in each batch only nine samples (three types of mixture × three replicates of each type of mixture) were allowed to run. However, for each concentration level we needed to run a total of 15 samples (five types of filtration materials × three replicates of each material). That means each concentration level needed to be split into two batches to run in the shaker. Even though the concentrations of initial solution were designed to be the same at the same pollutant concentration level, the actual chemical concentrations of initial solutions among separated batches were slightly different due to variations in weighting chemicals. However, the variations between batches were smaller than the variations between concentration levels. We treated the mixtures from the same concentration level together to be compared with the solutions from other concentration levels. After 24-hour shaking, we expected that the adsorption process reached equilibrium. The concentration difference between initial solution and equilibrium solution was used to calculate the amount of chemicals adsorbed on filtration materials by Equation 4.1:

$$q_e = \frac{V \times (C_0 - C_e)}{W} \tag{4.1}$$

Where q_e is the amount of chemicals adsorbed on filtration materials; V is the volume of solution, 250 ml; C_0 is the initial concentration of synthesized solution; C_e is the equilibrium concentration after 24 hours shaking; and W is the weight of filtration material, 2.5 g.

4.2.2.3 Column leaching experiment

Leaching of metals and nutrients was evaluated to quantify the pollutant removal efficiencies of different filtration materials under dynamic conditions. Laboratory-synthesized solutions, which were designed to simulate the maximum pollutant contents in Minnesota stormwater (pollutant concentration level L2 in Table 4.4), was continuously applied to each column at around 0.1 in/hr, the approximate average rainfall rate in Minnesota. Because the slowest mist sprayer has a flow rate much higher than 0.1 in/hr, we controlled the inflow pump to run 15 seconds every hour to achieve a rough inflow rate of 0.1 in/hr. The experiment was conducted in 20 PVC columns (internal diameter: 3 in) in two batches in two separate weeks due to space limitations (Fig. 4.3). Each batch was performed for 5 – 7 days in order to collect 5 – 8 250 ml bottle samples from each column. Chemical concentrations of inflow solutions in these two batches were slightly different (Table 4.5 for detailed inflow concentrations). The inflow and leachate solutions collected from columns were filtrated through 0.45 µm membrane, and the chemical concentrations in the supernatant were measured in the laboratory.

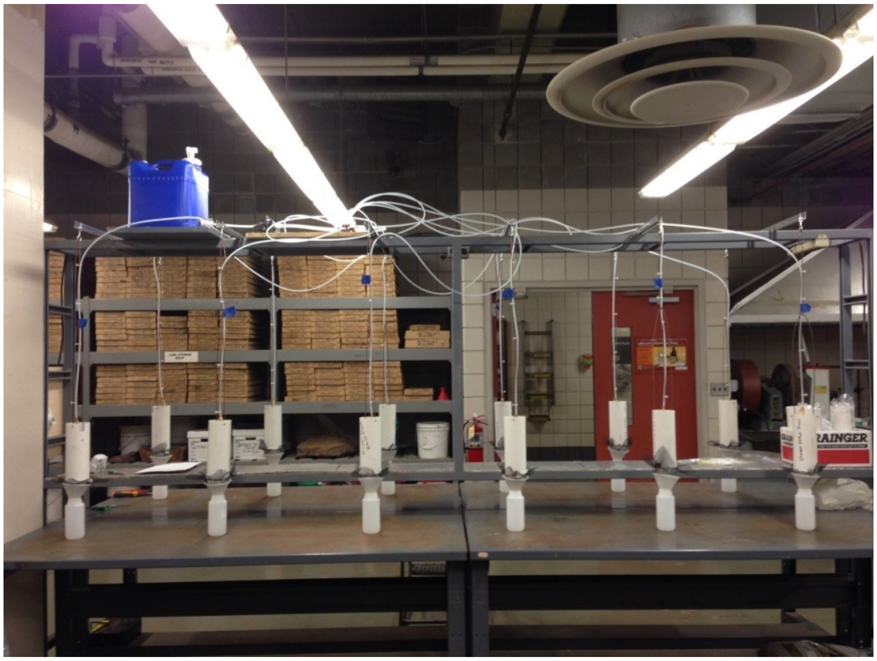


Figure 4.3 Column leaching experiment apparatus. This picture shows the first batch when 12 columns were used.

Table 4.5 Chemical concentrations of inflow solutions used for the leaching experiment.

Column no.	Cu, µg/L	Pb, µg/L	Zn, µg/L	PO4, µg/L
1-12	642	1036	777	4699
13-20	560	1000	737	5290

These PVC columns were filled with filtration materials at different volumetric proportions to a 6-inch depth. Each column is composed of 50% organic material and another 50% inorganic media (Table 4.6). Each type of media was designed to be three levels: 0%, 25%, and 50%.

The filtration material compositions for the column leaching experiments were designed by factors. Here factors are the types of filtration materials and volume proportion. To evaluate the effects of factors, a multiple linear regression model was fitted by using material types and volumetric proportion levels (0%, 25%, and 50%) as predictors and leachate concentrations of pollutants as the response variable. If the model coefficient of material or volume percentage level was significant, we would conclude that the material or the volume percentage can significantly change leachate outflow response. During the experiment we separated infiltration materials into an organic group (muck + one of commercial peat, compost, and salvage peat) and an inorganic group (sand, taconite tailings), and each group had a total volume percentage totaling 50%. That means one material in each group (organic or inorganic group) can be predicted by other materials in the same group. For example, if the total volume percentage of salvage peat (or compost, or commercial peat) was 25%, we know that another 25% of organic material should be muck. If one column was filled with 50% taconite tailings, there should be no sand in this column because the total volume proportion of taconite tailings and sand should be 50%. In order to avoid multicollinearity, one material of each organic or inorganic group must be dropped from the analysis. The coefficient for the dropped factor will be explained by the model intercept. In this study, we dropped “muck” and “sand” factors and used four other factors (compost, peat, commercial peat, and taconite tailings). The model fitting was performed in R 3.3.0 using the lm function in the basic R package.

Table 4.6 Volume percent of filtration materials used in each column for leaching experiment.

Column No.	Organic materials				Inorganic materials	
	Compost	Muck	Peat	Commercial peat	Taconite tailings	Sand
1		25	25			50
2		25	25		25	25
3			50		25	25
4		25	25		50	
5			50			50
6			50		50	
7	50				25	25
8	25	25			25	25
9	50					50
10		50				50
11	50				50	
12	25	25				50
13		50			25	25
14		50			50	
15		25		25		50
16		25		25	25	25
17				50	25	25
18		25		25	50	
19				50		50
20				50	50	

4.2.2.4 Chemical Measurement Procedure

Chemical concentrations for solutions collected from batch and column leaching experiments were measured using standard laboratory test methods. Table 5 presents the standard procedures that were followed.

Table 4.7 Laboratory test methods (APHA, 2012; EPA, 1978).

Parameters	Measurement Type	Equipment Model Number	Standard Procedure
pH	pH meter		APHA standard method 4500
Phosphate, nitrate	Ion chromatography (IC) for solutions from batch experiment Colorimetric analyzer for phosphate from column experiment	Metrohm 881	APHA standard method 4110 EPA method 365.3
Copper, iron, lead, zinc	Atomic absorption spectrophotometry (AAS)	Shimadzu AA-6300	APHA standard method 3110

4.2.3 Biological

Biological testing focused on the ability of study materials to grow and support vegetation.

The selected compost, peat, and soil treatment media were evaluated using several tests to determine their potential to sustain plant growth. Preliminary CO_2 respiration tests were conducted in containers to determine compost maturity and soil health. Standardized seed germination and seedling growth trials followed to determine any potential toxicity. Media passing these first tests were further evaluated in a greenhouse. Greenhouse studies were conducted on selected media using fast-growing plants such as radish and oats to determine their ability to support plant survival and growth.

4.2.3.1 Compost Maturity and Soil Respiration

The Solvita® measurement system developed at the Woods End Laboratories is a rapid method to determine compost maturity (Woods End Laboratories, 2016). With this method compost biological activity is determined by measuring carbon dioxide (CO_2) and ammonia (NH_3) emissions from a sample enclosed in a sealed container. Specially formulated gel probes placed within the container react to the concentrations of CO_2 and NH_3 gases resulting in a color change. After a 24-hour period, the gel color is compared with a color chart or read with a digital color reader to determine concentrations of these gases. High concentrations of CO_2 and NH_3 are indicators of immature, unstable compost. The Solvita® system can also be used to determine soil CO_2 respiration, an indicator of soil health and potential productivity.

Compost, peat, and soil media selected for this project were evaluated using the Solvita® measurement system. Three replications of each treatment media were analyzed. A digital color reader was used to determine concentrations of CO_2 and NH_3 gases. Results for compost and other media were compared to tables provided by Solvita® to evaluate compost maturity, determine soil respiration activity, predict potential nutrient mineralization, and assess if media is suitable for plant establishment and growth.

4.2.3.2 Seed Germination and Growth

In addition to the Solvita® measurement system, compost, peat, and soil media were evaluated using plant bioassays. Compost that has not been completely matured can be detrimental to plant growth. Seed germination maturity tests have been developed for evaluating compost to ensure its benefit to plants (University of Florida, 2011). Contaminants such as pesticides or other toxic substances can also be found in compost or other soils. Toxicity tests have been developed to determine their presence and effect on plant growth (ASTM, 2014; US Composting Council, 2015). These tests generally consist of plant bioassays using seeds of fast growing plants such as lettuce or radish grown on the substrates to be evaluated. Plant growth characteristics such as seed germination, root elongation, and seedling vigor are compared to a control to determine the safety of these substrates. For this study, several plant bioassays were conducted to assess compost, peat, and soil media suitability for plant growth.

4.2.3.3 Phytotoxicity Testing

The "suitability to grow" test is currently used by MnDOT to assess media for plant growth potential (Stenlund, 2015). In this two-part test, glass quart canning jars are half filled with moistened media. A good loam topsoil or commercial soil-less mix is used as a control. In the first part of the test, a filter paper is placed on the media surface and 10 – 25 seeds of a fast-growing plant such as lettuce are placed on top of the filter paper. The jar is then sealed and left at constant temperature in a growth chamber for 2 – 7 days. At a given end point, the number of seeds that have germinated are counted and compared to the control. Three replicates of each media were tested.

The second part of the test is a repeat of the first, with the filter paper omitted and the jar left uncovered. The seedlings are observed to determine germination and unusual leaf curling, tip browning, or stunting compared to the control that may indicate immature compost or other phytotoxic substances in the media.

4.2.3.4 Greenhouse Trials

Greenhouse trials were conducted to more definitively determine the ability of the compost, peat, and soil treatment mixtures to support vegetation on bioslopes/bioswales in field applications. Mixtures were placed in containers and seeded with fast-growing radish and oats. At least three replicates of each mixture were tested. The containers were randomly placed in a greenhouse and watered regularly to ensure moisture conditions suitable for plant growth. Monitoring included plant germination and total root and shoot dry weight.

4.3 CONCLUSION

Chapter 4 outlines the methods that were used to characterize media for water retention and treatment in stormwater BMPs. Methods were selected on the basis of reproducibility and applicability to various media. The proposed treatment media mixtures were evaluated using the selected tests to determine their infiltration capacity, pollutant removal capability, and ability to support vegetation.

CHAPTER 5: LABORATORY RESULTS AND DISCUSSION

5.1 INTRODUCTION

Chapter 5 provides results classifying and characterizing materials used as filter media for stormwater bioinfiltration devices. Physical, chemical and biological properties, and performance in stormwater treatment of five filtration materials (compost, commercial peat, salvaged peat, muck, and taconite tailings) were evaluated through laboratory experiments. Media characterization was summarized based on civil engineering, environmental engineering, and biological disciplines.

5.2 CIVIL ENGINEERING

Individual treatment media was characterized in order to inform filter media mix design and provide a comparative analysis to currently specified filter media, i.e., sand and compost. Knowledge of individual filter media is also necessary for the meaningful analysis of filter media mix performance with regard to its constituents. The civil engineering portion of this research focused on relevant geotechnical and hydrological engineering properties such as particle size distribution, compaction characteristics, soil moisture content, and hydraulic conductivity. The following sections describe the testing protocols for determining the geotechnical and hydraulic properties.

5.2.1 Classification

Soil classification was conducted in order to aid in the identification of similar materials for use in the field or reproducibility in future laboratory tests (Table 5.1). Taconite tailings, sand, and muck were classified according to ASTM D2487 (ASTM, 2011). Atterberg limits were determined in accordance with ASTM D4318 (ASTM, 2010b). Liquid and plastic limits were determined to be 64% and 38%, respectively.

Table 5.1 United Soil Classification System (USCS) soil classification of the tested biofilter materials.

Material	USCS Classification
Taconite Tailings	Well-graded sand (SW)
Sand	Poorly-graded sand (SP)
Muck	Sandy organic clay (OH)
Peat	Pt

MnDOT specifications for Grade 2 compost ensure proper identification, eliminating the need for further classification. Commercial compost from a MnDOT-certified distributor was tested by the U.S. Composting Council (Laboratory Number: 5050829-1/1) to ensure that properties are in compliance with a MnDOT Grade 2 compost classification. Peat was categorized as sapric, high ash, slightly acidic, slightly absorbent peat according to ASTM D4427 (ASTM, 2013). ASTM D4427 required the completion of several additional tests as summarized in Table 5.2.

Table 5.2 Summary of test results for classification of peat (ASTM, 2013).

Parameter	Standard	Results
Fiber Content	ASTM D1997-13 Standard Test Method for Laboratory Determination of the Fiber Content of Peat Samples by Dry Mass	32%
Ash Content, pH	ASTM D2974-14 Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils	61%, 6.5
Absorbency	ASTM D2980-04 (2010) Standard Test Method for Volume Mass, Moisture-Holding Capacity, and Porosity of Saturated Peat Materials	204%

5.2.2 Particle Size Distribution

Determination of the particle size distributions (Figure 5.1) of taconite tailings, sand, and muck were conducted according to ASTM D422. The uniformity coefficient (C_u), coefficient of gradation (C_c), percent finer than the # 200 sieve, and effective diameter at 10%, 30%, and 60% passing (D_{10}, D_{30}, & D_{60}, respectively) of sand and taconite are presented in Table 5.3. Particle size distributions were used both for soil classification and for MnDOT specification compliance.

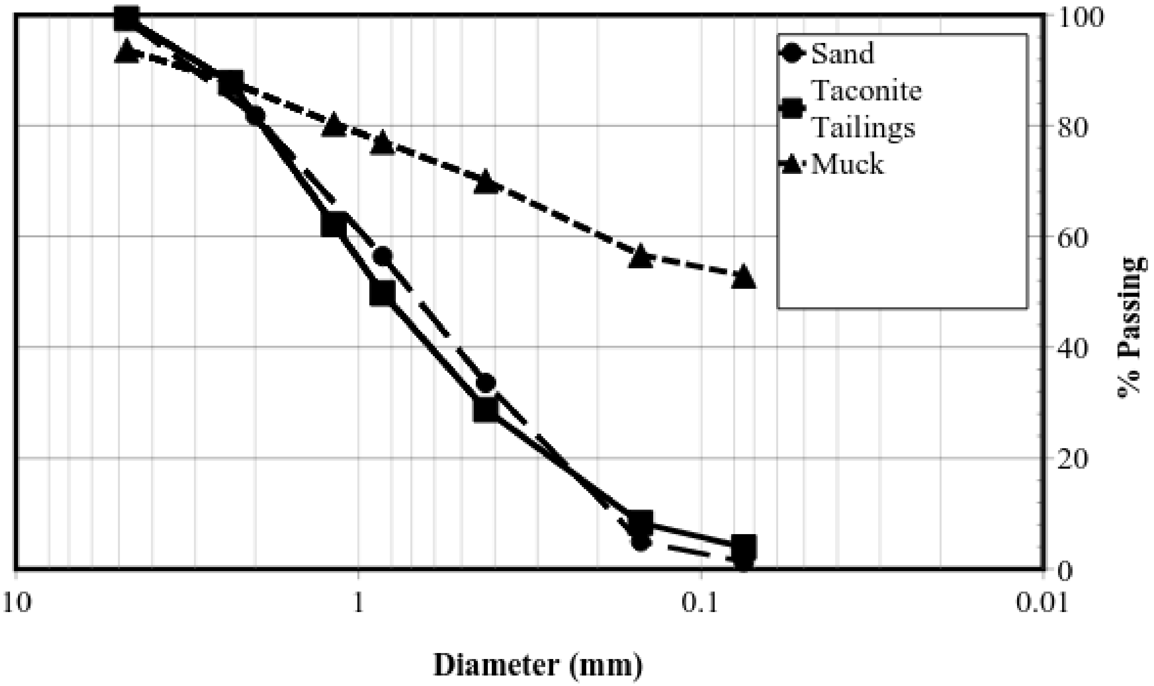


Figure 5.1 Particle-size distributions for sand, muck, and taconite tailings.

Table 5.3 Grain-size parameters for sand and taconite tailings.

	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	% finer than #200 sieve
Sand	0.18	0.39	0.98	5.60	0.89	1.26
Taconite Tailings	0.17	0.45	1.20	7.06	0.99	3.91

5.2.3 Compaction Characteristics

Results from the standard Proctor test for the determination of relative density and optimum moisture contents (Table 5.4) indicate similarity between taconite tailings and sand (Figure 5.2). Peat and compost are also similar with a relatively low maximum dry density. Peat was tested at seven different moisture contents and was found to have a maximum density of 5.7 kN/m^3 at an optimum moisture content of 75%. As the moisture content of peat diverged from 75%, density decreased to between 4.5 and 5 kN/m^3 (Figure 5.3). Muck had the highest maximum dry density, at 13.4 kN/m^3, of the three organic soils tested (Figure 5.4).

Table 5.4 Maximum dry density and optimum moisture content of individual biofilter media.

	Maximum Dry Density (kN/m^3)	Optimum Moisture Content (%)
Sand	19.1	13%
Taconite Tailings	19.4	8%
Compost	6.5	35%
Peat	5.7	75%
Muck	13.4	20%

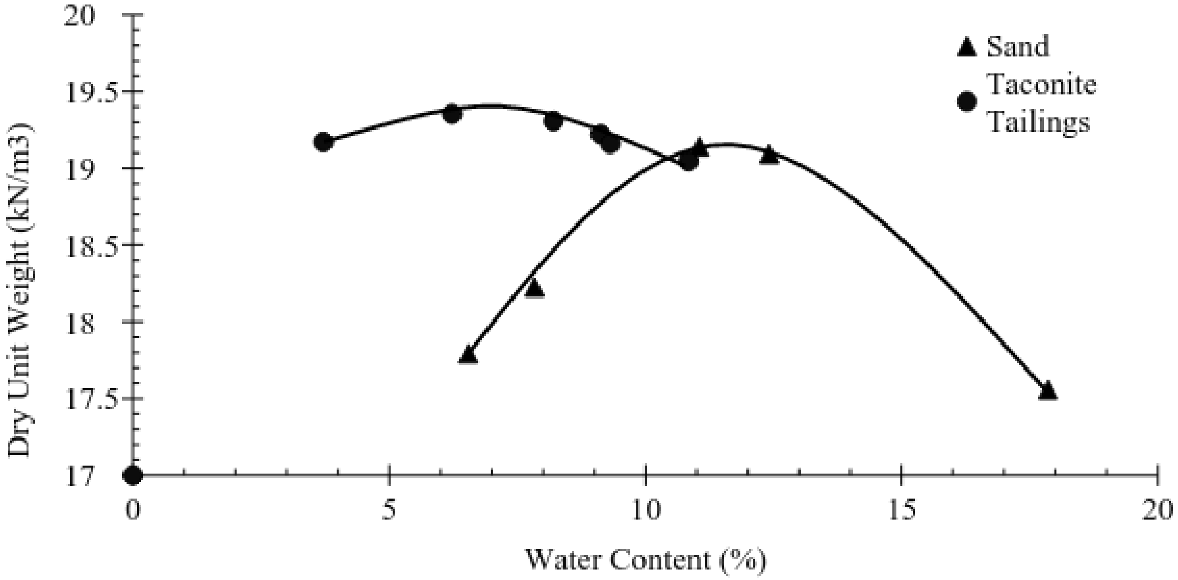


Figure 5.2 Standard Proctor compaction curves for sand and taconite tailings.

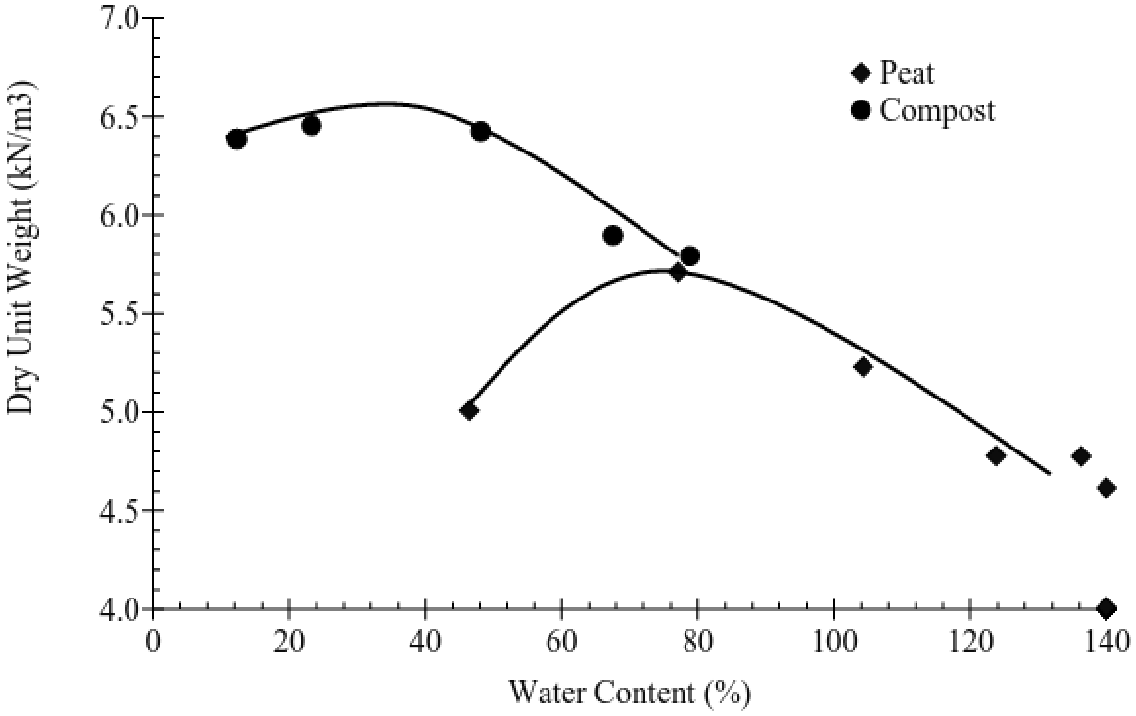


Figure 5.3 Standard Proctor compaction curves for peat and compost.

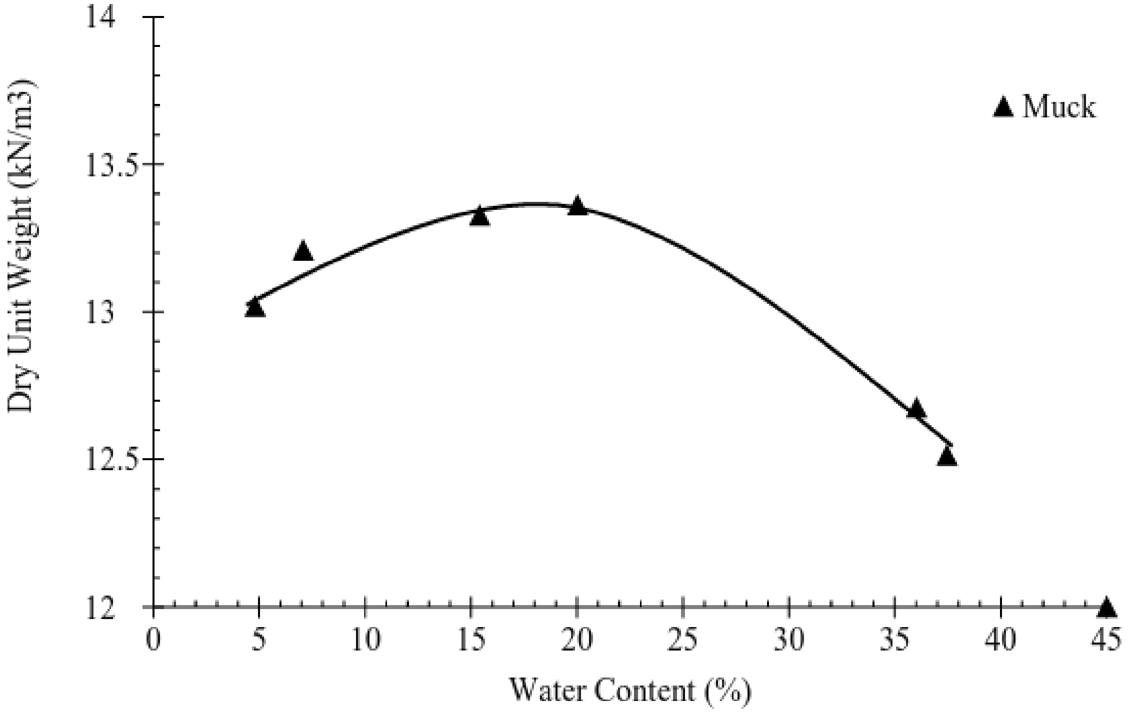


Figure 5.4 Standard Proctor compaction curves for muck.

5.2.4 Hydraulic Conductivity and Water Holding Capacity

The hydraulic conductivity at 85% of maximum dry density was determined by constant head test (ASTM D2434) for taconite tailings and sand. Muck, peat, and compost were also tested at a density equal to 85% of the maximum dry density using a falling head test (Germaine and Germaine, 2009) (Table 5.5). Preliminary results show that taconite tailings have a higher conductivity than sand. The hydraulic conductivity of peat is higher than that of compost by two orders of magnitude. This may be attributed to the fibrous structure of peat, which increases the amount and connectivity of pores in the soil structure. Muck was observed to have a relatively low conductivity, which is consistent with its high fines content.

Table 5.5 Saturated hydraulic conductivity of individual biofilter media.

Media	Saturated Hydraulic Conductivity (cm/sec)
Sand	$6.0*10^{-3}$
Taconite Tailings	$1.0*10^{-2}$
Compost	$4.5*10^{-5}$
Peat	$7.7*10^{-3}$
Muck	$7.0*10^{-6}$

Construction specifications (MnDOT, 2016) call for a mixture of 60 – 80% sand with 20-40% MnDOT Grade 2 compost. The hydraulic conductivity of these specified mixtures served as upper and lower bound performance criterion. Two alternative media mixtures were designed to contain a 50:40:10 ratio of inorganic aggregate, peat, and muck. Results from the constant head tests, shown in Table 5.6, indicated that the hydraulic conductivity of sand-compost mixtures can be matched using alternative media. These preliminary results demonstrate the ability of alternative filter media to meet hydraulic conductivity performance standards.

Table 5.6 Saturated hydraulic conductivity of biofilter media mixtures.

Media Mixture	Saturated Hydraulic Conductivity (cm/sec)
40% Sand, 60% compost	$1.5*10^{-4}$
50% Sand, 40% Peat, 10% Muck	$1.7*10^{-4}$
50% Taconite Tailings, 40% Peat, 10% Muck	$1.3*10^{-3}$
60% Sand, 40% compost	$1.5*10^{-3}$

In addition to standard constant and falling head experiments, laboratory infiltration experiments were conducted to determine the infiltration curve into dry media mixtures. These experiments were conducted to demonstrate unsaturated hydraulic conductivity rates and to study how the observed hydrophobia of dry peat affects infiltration and water absorption. Results from these experiments shown in Figure 5.5 indicated that peat is more effective than compost at improving infiltration rates and infiltration capacity when added as an amendment to sand in a ratio of 50:50 sand to compost or peat.

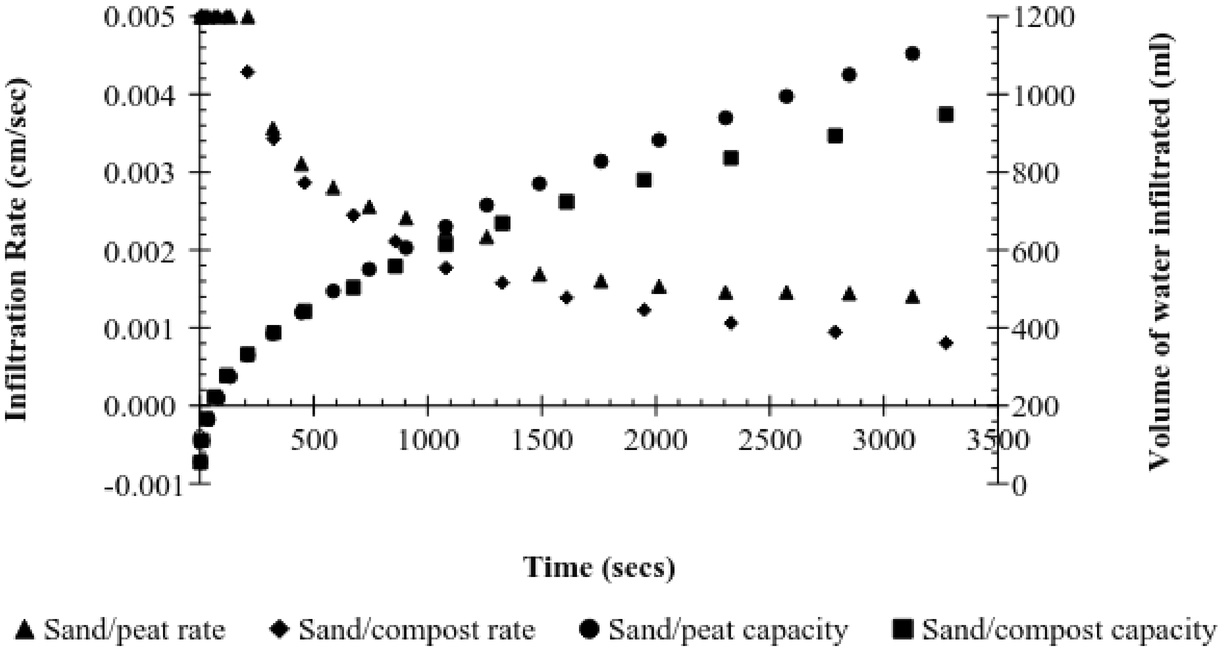


Figure 5.5 Infiltration rate and capacity of 50:50 mixtures of sand and peat or compost at 85% relative density.

Moisture holding capacity of the study materials was examined at saturation and at field capacity, defined by applying 33 kPa pressure until steady-state outflow is reached, using a flow-through pressure cell apparatus. This test was conducted according to procedures outlined by the University of Connecticut Department of Civil and Environmental Engineering (Figure 5.6). Cells containing soil compacted to 85% relative density were deemed saturated when steady-state flow was reached during hydraulic conductivity tests. Once soil was saturated, the moisture content was calculated by mass. Next, air at a pressure of 33kPa was applied to the cell until steady-state outflow was reached, at which point moisture content was determined according to ASTM D2216-10 (ASTM, 2010a). Results from individual media tests show that peat holds more moisture than muck or compost and that peat and compost have a similar ability to increase the moisture-holding capacity of sandy soil.

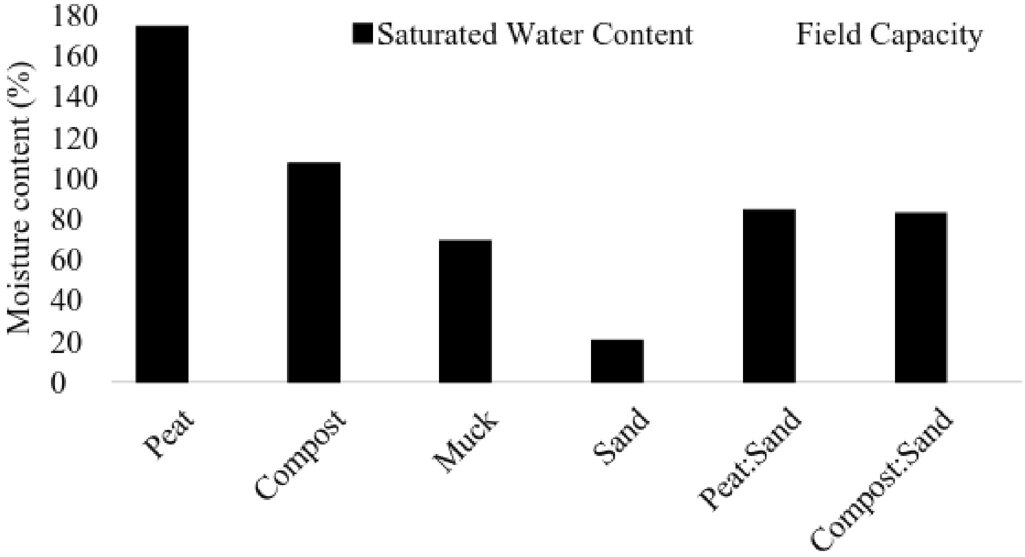


Figure 5.6 Water-holding capacity of study materials at saturation and field capacity.

5.2.5 Conclusions

Individual media including sand, taconite tailings, compost, peat, and muck were tested for grain-size distribution, compaction characteristics, hydraulic conductivity, and moisture-holding capacity. Media mixtures were then mixed by volume and tested for hydraulic conductivity, infiltration rate, infiltration capacity, and moisture-holding capacity for comparison to currently specified mixtures of sand and compost. From these preliminary results, the following conclusions were drawn.

Sand used for this research is poorly-graded (SP), while the taconite tailings are well-graded (SW). Taconite tailings and sand have maximum dry densities of 19.4 kN/m^3 and 19.1 kN/m^3, respectively. The hydraulic conductivity of sand was 6.0*10^{-3} cm/sec, while taconite tailings had a conductivity of 1.0*10^{-2} cm/sec. Due to their similar physical characteristics, the hydraulic and geotechnical performance of these materials is similar, making them interchangeable from a civil engineering perspective.

Peat materials performed as well or better than compost in all hydraulic and geotechnical tests. Peat has a high moisture-holding capacity, hydraulic conductivity, and performs similarly to compost when added as an amendment to sand. While the peat samples used in this research performed well, previous literature reviews have revealed large variability in peat's hydraulic properties depending on origin and degree of decomposition. Due to this variability, it may be prudent to evaluate peat materials on a case-by-case basis when used in stormwater treatment devices.

The material described as muck and used in this research classifies according to the USCS as sandy organic clay. Muck has deleterious qualities that preclude its recommendation for use in biofilter media mixtures including a low hydraulic conductivity and low workability. The high clay content of the studied muck material impedes infiltration, which may increase the probability of Hortonian overland flow when used in bioslopes. Additionally, muck material was found to be difficult to mix, adheres to equipment, and when dried becomes hard and impermeable.

5.3 ENVIRONMENTAL ENGINEERING

Chemical content of filter materials will affect leachate water quality, nutrient supply for plants, and pollutant removal efficiency. To evaluate the pollutant removal efficiencies or potential release of contaminants from studied filtration materials, two types of environmental experiments, including batch and column leaching experiments, were performed in the laboratory to characterize chemical properties and pollutant adsorption capacities under static and dynamics conditions for individual and mixed filtration materials. The environmental parameters examined in the experiments included pH, nutrient content (nitrate, phosphate), and heavy metal concentrations (copper, iron, lead, zinc).

5.3.1 Batch experiments

The synthesized solution was prepared with laboratory chemicals such as $NaH_2PO_4{\cdot}H_2O$. The proton contained within $NaH_2PO_4{\cdot}H_2O$ added acidity to the solution; the resulting pH values of initial solutions were between 4.47 and 5.4 and decreased with increasing concentration levels. However, the acidity of the initial solution was sufficiently neutralized by compost, muck, salvage peat, and taconite tailings, and the pH values of mixture solutions after 24-hour shaking were between 6 and 9 (Figure 5.7), a pH range required by water standards. Commercial peat was acidic as reported, and the solution pHs were around 4.

To examine the adsorption capacity of each filtration material, the concentrations of studied chemicals in the solutions were compared before and after 24-hour shaking. The selected five filtration materials did not exhibit significant effect in removing nitrate and phosphate (Figure 5.8). In contrast, compost released a large amount of nitrate (>90 mg/L) and a small amount of phosphate (<10 mg/L). Salvaged peat also exported a little nitrate (~ 3 mg/L) but can adsorb a little phosphate (~9 mg/L) at a high inflow concentration.

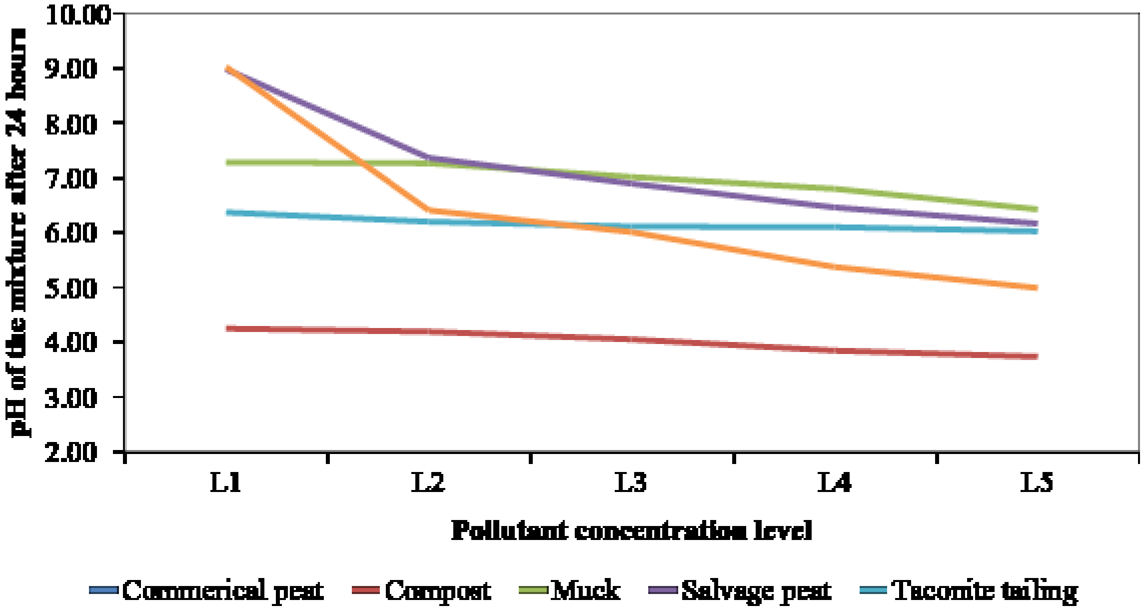


Figure 5.7 The pH of the mixture of synthesized solutions and filtration materials after shaking for 24 hours at 100 rpm.

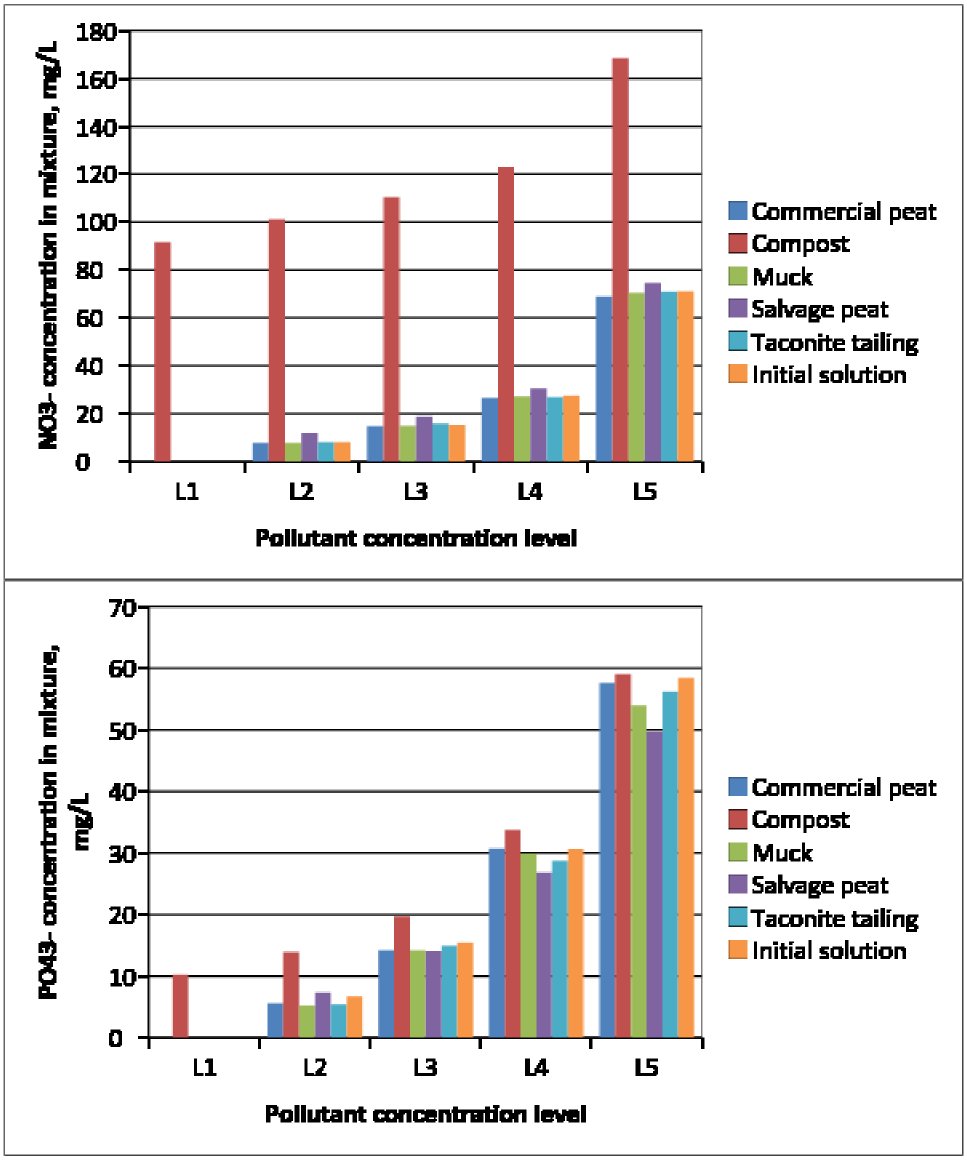


Figure 5.8 Concentrations of nitrate and phosphate before (initial solution bar in the chart) and after 24-hour shaking for the mixture.

Compared to the nutrient removal, most materials can significantly remove metals from water. In general, more than 80% of metals were removed from the solution by peat and compost, and muck can remove around 50% of metals (Figure 5.9). Salvaged peat had the largest adsorption capacity of copper and zinc compared to other materials. Commercial peat and compost had good performance in retaining metals, and muck had intermediate removal capacities for these two metals. Taconite tailings cannot adsorb copper and zinc but had the largest retention capacity of lead, possibly due to co-precipitation by iron hydroxide.

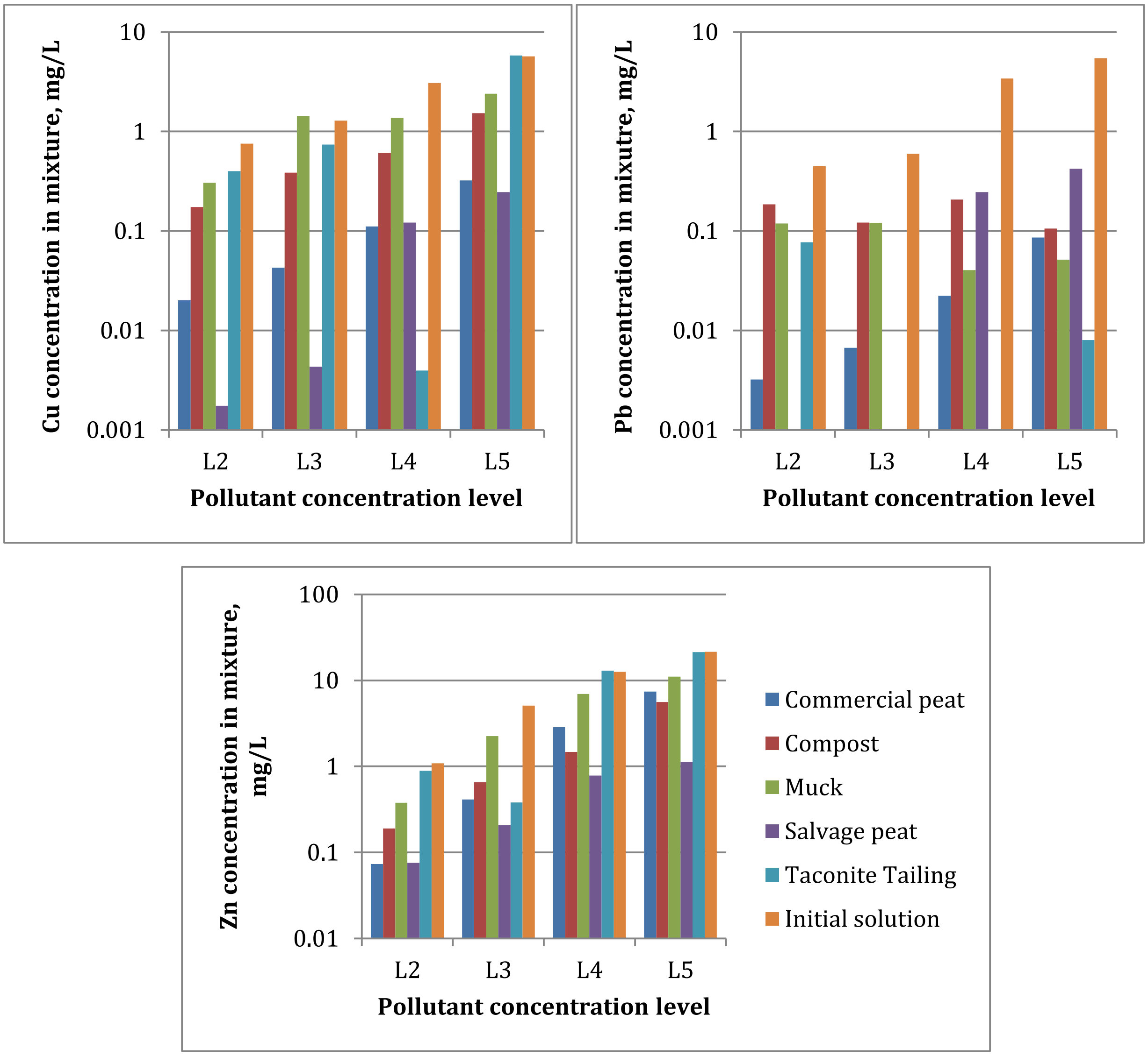


Figure 5.9 Concentration of Cu, Pb, and Zn before (initial solution bar in the chart) and after 24-hour shaking for the mixture. Pollutant concentration level represents the initial solution concentration level in Table 4.4.

5.3.2 Leaching experiments

Chemical concentrations of leachate solutions collected from columns composed of a mixture of organic and inorganic filtration materials were measured and compared with inflow concentrations to determine chemical retention capacities under dynamic conditions.

5.3.2.1 Leachate color and suspended solids

Each leachate collected was visually examined to evaluate the effluent color and roughly compare the suspended solids content. Outflow from compost typically had a large amount of suspended solids, and the solution appeared dark brown in color (Figure 5.10). Muck exported clay material into the leachate, leading to relatively high suspended solids concentrations. Both salvaged peat and commercial peat did not export much solids to the outflow, but the high organic acid content in commercial peat resulted in a yellow outflow. Iron in taconite tailings caused the leachate color to be red.

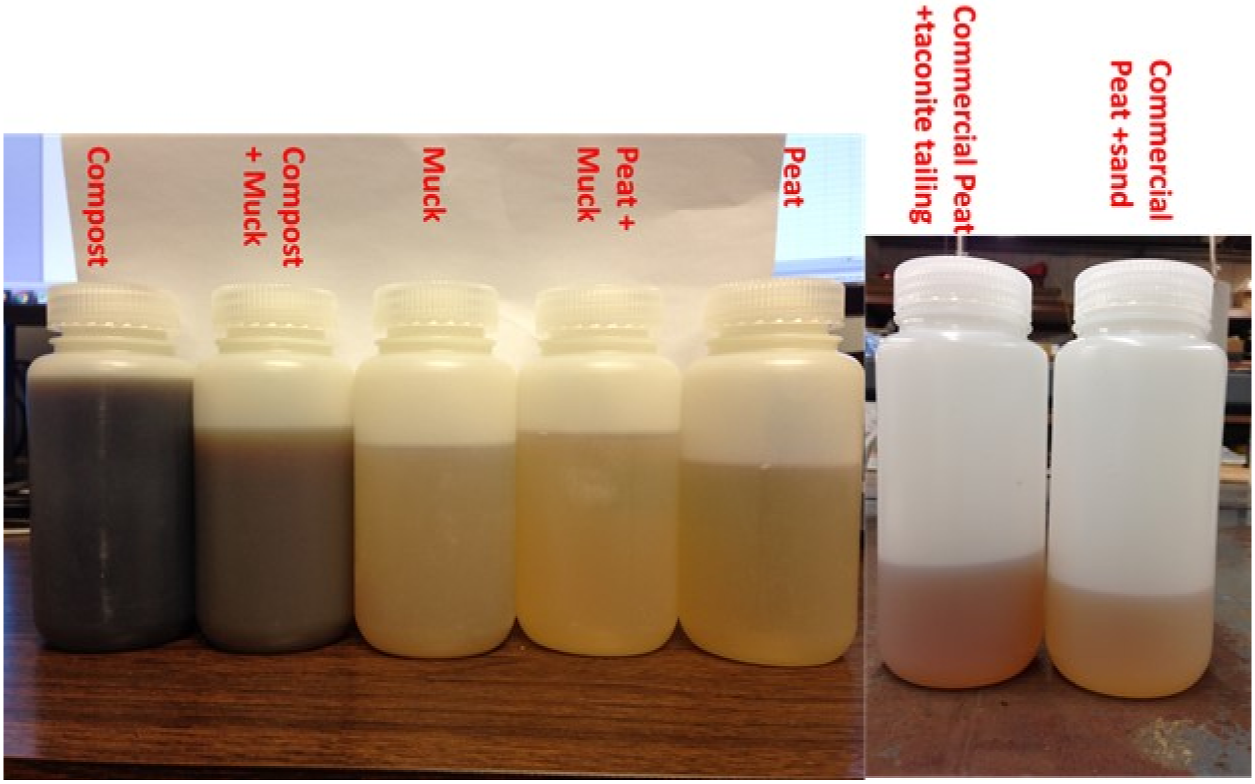


Figure 5.10 Typical leachate solutions after flowing through different filtration materials.

5.3.2.2 Time trend

The leaching experiment was designed to collect 5 – 8 bottles of leachate. Concentrations of Cu, Zn, and PO_4 in leachate samples fluctuated but generally declined over time (Figures 5.11 and 5.12). Lead concentrations in the outflow were very low, even below the detection limit (1 µg/L); therefore, lead was excluded from the analysis. Concentrations of copper and zinc in the outflow of several columns may have reached a stable level, while most of the columns did not have stable outflow concentrations during the experiment period. Because there were no obvious stable outflow concentrations achieved for most columns, the chemical concentrations were averaged across the time period to be used to evaluate treatment efficiencies of different materials.

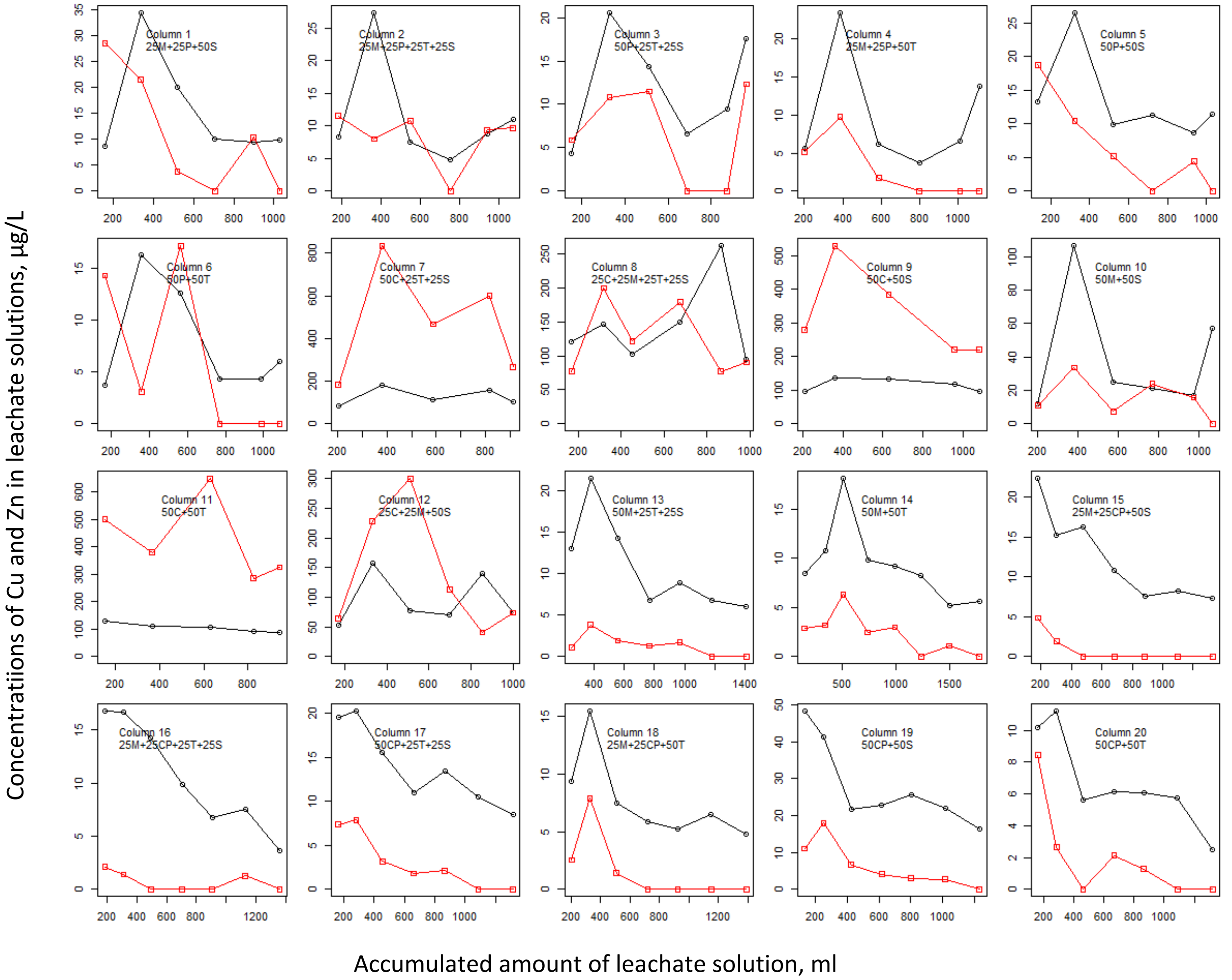


Figure 5.11 Changes of Cu (black) and Zn (red) concentrations in leachate solutions along with accumulated outflow collected from 20 columns. Column compositions are shown in graph titles as volume percentages and abbreviations (C=compost, CP=commercial peat, M=muck, P=peat, T=taconite tailing, S=sand) for filtration materials.

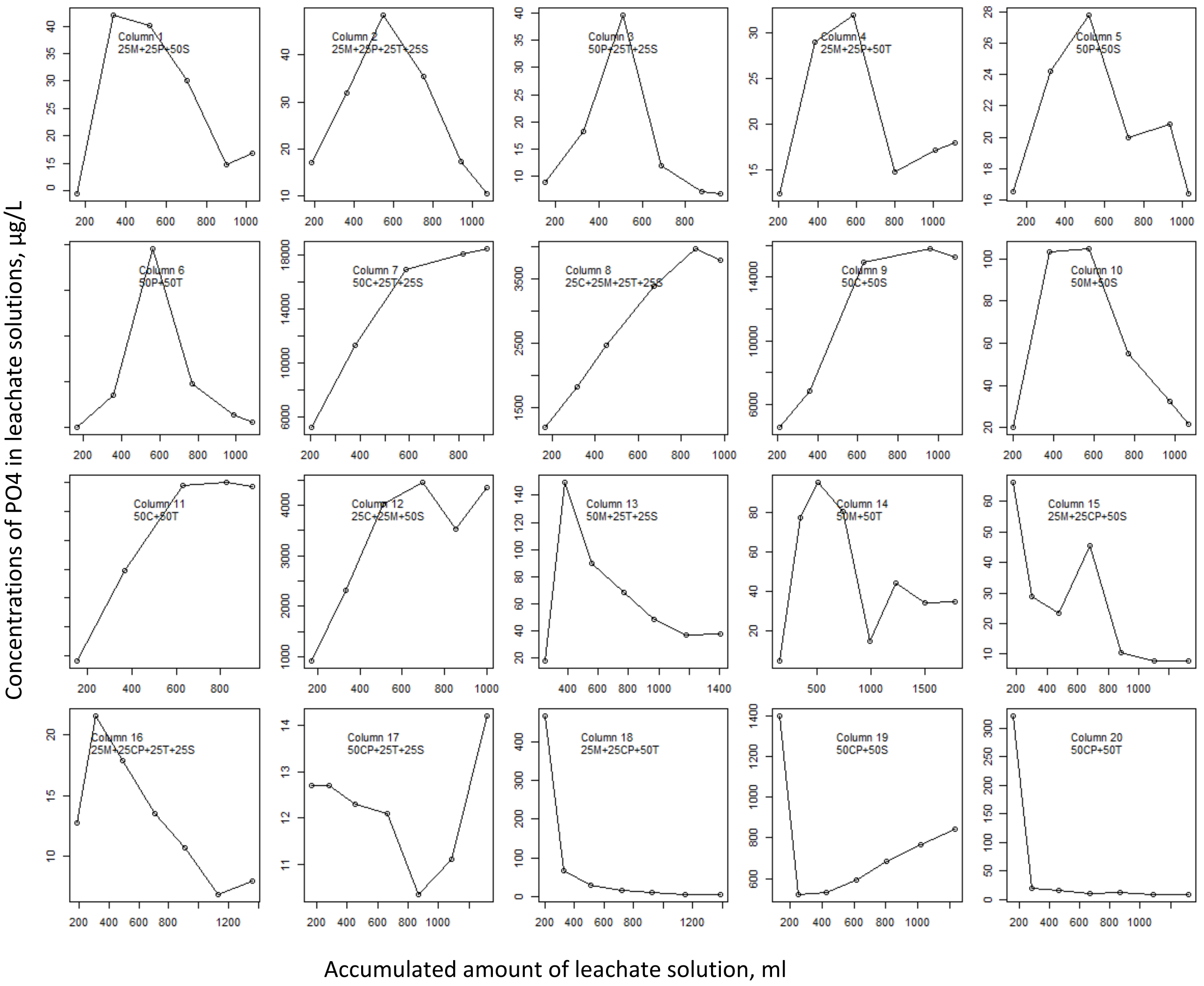


Figure 5.12 Changes of PO₄ concentrations in leachate solutions along with accumulated outflow collected from 20 columns. Column compositions are shown in graph titles as volume percentages and abbreviations (C=compost, CP=commercial peat, M=muck, P=peat, T=taconite tailing, S=sand) for filtration materials.

5.3.2.3 Adsorption efficiencies under dynamic conditions

The concentrations of Cu, Zn, and PO_4 (Figures 5.11 and 5.12) demonstrated a remarkable difference among columns, especially the outflow from columns containing compost (Columns 7, 8, 9, 11, and 12), which tended to have the largest concentrations. Multiple regression models were developed by using filtration types and volumetric proportion of each material as predictor variables and outflow chemical concentrations as response variables. We averaged the outflow chemical concentrations for each column to gain 20 rows of data (one row per column, compositions shown in Table 4.6 in Chapter 4) and used the averaged values as response variables to be linked with the composition of filtration materials in each column to perform the multiple regression modeling.

Model fit coefficients are provided in Table 5.7. The baseline (the intercept in the model) for each column is the concentration of outflow from column with 50% muck and 50% sand. Muck was used as the baseline here because the filtration materials in columns were comprised of muck and one other organic material. Negative or positive coefficients for factors need to be added with the intercept to get predicted values for filtration materials with compositions listed for that factor. For example, the pH of outflow from the column filled with compost (25%) +muck (25%) + sand (50%) is expected to be 8.44 – 0.18 = 8.26.

Table 5.7 Parameter coefficients of linear regression models for pH, Cu, Zn and PO_4 concentrations (unit: µg/L) in leachate solutions. Significant coefficients ($p<0.05$) are in bold.

Factor	pH	Cu	Zn	PO_4	Compositions in factor
(Intercept)	***8.44***	***22.43***	-2.45	-99.22	muck=50%,sand=50%
Compost25	-0.18	***96.98***	***124.99***	***3024***	compost=25%,muck=25%, sand=50%
Compost50	-0.52	***95.93***	***401.70***	***13153***	compost=50%, sand=50%
Peat25	0.01	-7.88	0.91	-31.93	peat=25%, muck=25%, sand=50%
Peat50	-0.39	-8.91	0.01	-37.42	peat=50%, sand=50%
Commercial.peat25	-0.15	-9.71	-5.20	-14.18	commercial peat=25%, muck=25%, sand=50%
Commercial.peat50	***-2.09***	-3.70	-2.40	220.99	commercial peat=50%, sand=50%
Taconite.tailings25	0.23	2.00	15.93	178.09	muck=50%, taconite tailings=25%, sand=25%
Taconite.tailings50	0.26	-9.02	10.38	288.18	muck=50%, taconite tailings=50%

Commercial peat can significantly reduce leachate pH; however, the reduction was dependent on the amount of commercial peat used. If 25% or less commercial peat was combined with muck, no significant pH reduction occurred. Solution pH values for leachate from compost or peat were slightly but insignificantly smaller than outflow from muck, while taconite tailings can increase outflow pH when compared with sand.

Leachate solutions from compost have significantly higher copper, zinc, and phosphate than all other organic materials (muck, peat, commercial peat). Comparing the parameter coefficients, we roughly estimated that the copper and zinc concentrations for compost leachate should be above 100 µg/L but below inflow concentrations (Cu ~ 500 µg/L and Zn ~ 700 µg/L). However, the effluent PO_4 concentration from column with 50% compost was 13 153 – 99.22=13 054 µg/L, which was significantly higher than inflow PO_4 concentration (around 5000 µg/L). The significant higher outflow PO_4 concentration indicated that decomposition of compost was exporting additional phosphate into the effluent. The high amount of phosphate export from compost indicates that compost application into stormwater treatment should be limit to small ratio, such as 7 – 10% as suggested by Minnesota storm manual.

Because of the large variation of data from compost columns, the effects of other filtration materials may be masked. Therefore, we excluded the columns with compost (five columns) and re-did multiple regression analysis for the remaining 15 columns. Again, commercial peat can significantly reduce outflow pH when 50% of commercial peat is included in the filtration materials (Table 5.8). Taconite tailings can reduce copper and zinc concentrations in leachate solution — in other words, enhance the metal removal. Taconite tailings also showed potential to enhance PO_4 removal as shown by negative coefficients, even though the coefficients are insignificant.

Table 5.8 Parameter coefficients of linear regression models for pH, Cu, Zn, and PO_4 concentrations (unit: µg/L) in leachate solutions (n=15). Different from the previous table, the solutions collection from compost-filled columns were excluded and the variable of compost factor was excluded from analysis. Significant coefficients ($p<0.05$) were in bold.

Factor	pH	Cu	Zn	PO_4	Compositions in factor
(Intercept)	***8.39***	***27.95***	***9.29***	150.96	muck=50%,sand=50%
Peat25	0.01	-7.88	0.91	-31.93	peat=25%, muck=25%, sand=50%
Peat50	-0.39	-8.91	0.01	-37.42	peat=50%, sand=50%
Commercial.peat25	-0.15	-9.71	-5.20	-14.18	commercial peat=25%, muck=25%, sand=50%
Commercial.peat50	***-2.09***	-3.70	-2.40	220.99	commercial peat=50%, sand=50%
Taconite.tailings25	0.31	***-10.04***	-3.91	-152.17	muck=50%, taconite tailings=25%, sand=25%
Taconite.tailings50	0.34	***-13.56***	***-5.03***	-132.10	muck=50%, taconite tailings=50%

5.3.2.4 Competitive adsorption of copper and zinc on organic materials

Removal efficiencies of metals are largely determined by the type of organic materials. Zn concentrations were compared with Cu concentrations in leachate samples for each column (Fig. 5.11). In general, Zn concentrations were higher than Cu concentrations after passing through columns with compost. In contrast, more copper was leached from other organic materials, including commercial peat, salvaged peat, and muck. This difference indicated that compost may have a higher affinity to copper than zinc, while peat or similar materials are preferential for zinc than copper.

5.3.2.5 Potential release of iron from compost and taconite tailings

The application of taconite tailings brings one concern — the potential release of Fe. In Minnesota, the total iron concentration limit is 300 µg/L for secondary drinking water (class 1B water). To determine how much Fe would be released from taconite tailings, we measured Fe concentrations of leachate solutions collected from taconite tailings and compost columns. The Fe concentrations of each column were averaged first, then compared by volumetric proportion of taconite tailings or compost (Figure 5.13). Most leachate solutions had iron concentrations below 300 µg/L, no matter if taconite tailings made up 25% or 50% of filtration materials. The highest iron concentrations were found in solutions collected from filtration materials which contained 50% compost (the right plot in Figure 5.13). This indicated that the combination of compost and taconite tailings may enhance the release of iron. This result led to another question: Was compost itself releasing iron? To answer this question, the iron concentrations of two mixture solutions (taconite tailings+DI water, compost+DI water) from batch experiments were examined (Figure 5.14). It clearly showed that taconite tailings and compost can release iron at around 1.8 and 4.8 µg/g, respectively.

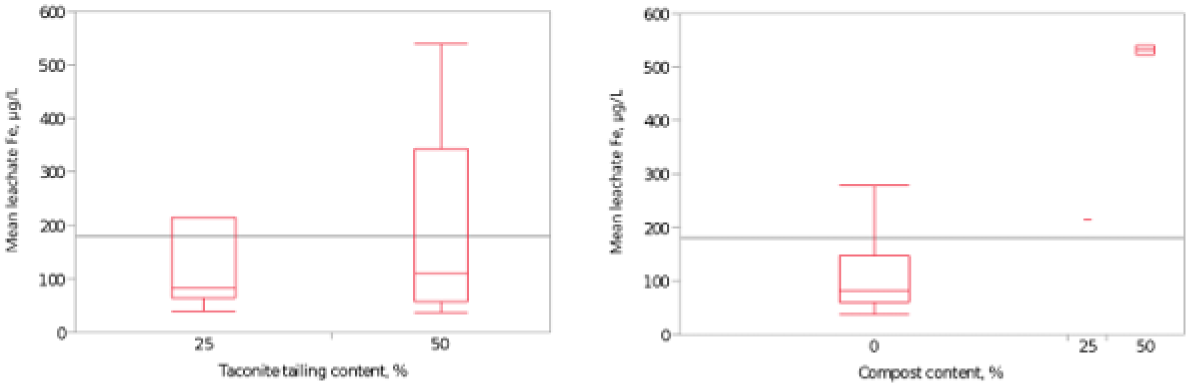


Figure 5.13 Mean Fe concentrations in leachate solutions of each column.

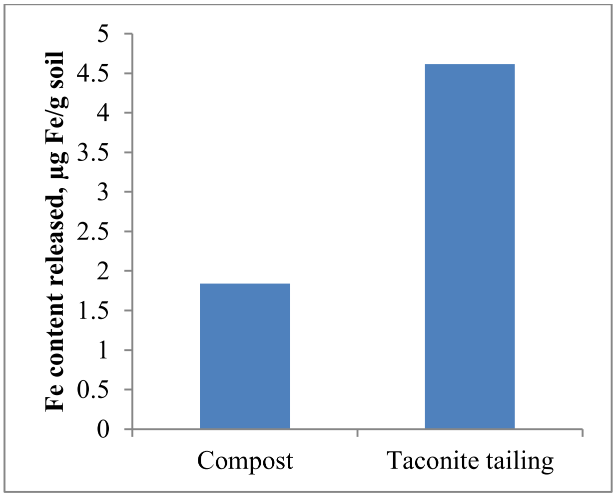


Figure 5.14. Fe content released to solution for the mixtures of 2.5 g compost or taconite tailing with 250 ml DI water.

5.3.3 Conclusions

Through batch and column leaching experiments, we observed that all organic materials can remove metals from solution at different efficiencies. Both salvaged peat and commercial peat have the largest removal efficiencies for metals. Compost had a large capacity to remove metals, but the removal efficiencies in leaching experiments were intermediate, probably due to the adsorption rate limit. Table 14 summarizes the performance of each of the filtration materials in pollutant removal. Commercial peat can significantly remove metals but lead to acidic outflow. Solutions treated by compost have several problems: dark brown color, high suspended solids, and potential release of Fe, NO_3 and PO_4.

Pollutant removal efficiencies of muck were intermediate when compared with other materials. Salvaged peat had the best performance in metal removal and exported relative clear drainage water. Taconite tailings may potentially enhance PO_4 removal.

Table 5.9 Summary of filtration material performance in the batch experiment and leaching experiment.

Filtration material	pH	Color and suspended solid	Metals removal	Nitrate and phosphate removal
Commercial peat	Significant pH reduction	Leachate yellow but clear	Yes, good	No
Compost	Neutral	Leachate brown and high suspended solids content	Yes, good in batch experiment but intermediate in leaching experiment	No, but added large amount of nutrients
Muck	Neutral	Clear, but large clay content	Yes, intermediate	No
Salvage peat	Neutral	Clear and no color	Yes, best removal efficiency	No
Taconite tailings	Neutral	Clear but red in color	No, except lead	Potentially enhance PO_4 removal

5.4 BIOLOGICAL

Biological testing focused on the ability of study materials to grow and support vegetation. The selected compost, peat, and soil treatment media were evaluated using several tests to determine their potential to sustain plant growth. These tests included: 1) MnDOT “Suitability to Grow” tests to determine any potential plant toxicity; 2) Solvita® carbon dioxide (CO_2) and ammonia (NH_3) respiration tests to determine compost maturity and soil health; 3) greenhouse growth studies to determine the effects of varying substrate mixtures on plant germination and dry matter production; and 4) chemical analysis of compost, peat, and muck to determine pH, organic matter, soluble salts, and macro- and micro-nutrients.

5.4.1 Phytotoxicity Testing

The “Suitability to Grow” test is currently used by MnDOT to assess media for plant growth potential (Stenlund, 2015). In this two-part test, glass quart canning jars were half filled with moistened media. A commercial soil-less mix was used as a control. In the first part of the test, a filter paper was placed on the media surface and 10 lettuce seeds were placed on top of the filter paper. The jars were then sealed and left in a growth chamber at constant temperature (25 °C) and 16 hours of simulated daylight. After seven days, the number of seeds that germinated were counted and the percent germination was calculated. Three replicates of each media were tested.

The second part of the test was a repeat of the first, with the filter paper omitted and the jar left uncovered. The seedlings were observed at seven days to determine the seedling survival percentage and document growth characteristics.

Results of the tests are presented in Table 5.10. Similar seed germination of over 90% occurred for peat, muck, sand, and tailings, and all actually performed better than the top soil control. Seed germination for compost was considerably worse, with less than 30%. Seedling survival was over 80% for peat, sand, tailings, and top soil, with over 50% for muck and 0% for compost. Seedling growth characteristics were normal for peat, tailings, and top soil but were stunted for muck and sand. Some compost seedlings were observed at 21 days, but germination still remained less than 40%.

Table 5.10 "Suitability to Grow" test mean germination and seedling survival for treatment media (n=3). Compost seedlings were also observed at 21 days due to no initial germination.

Substrate	Seed Germination %	Seedling Survival %	Growth Characteristics
Peat	96.7	86.7	Green normal seedlings
Muck	93.3	56.7	Stunted seedlings
Compost	26.7	0.0	No seedlings observed at 7 days 36.6% at 21 days
Sand	96.7	83.3	Stunted seedlings, some green
Tailings	96.7	83.3	Green normal seedlings
Top Soil	86.7	86.7	Green normal seedlings

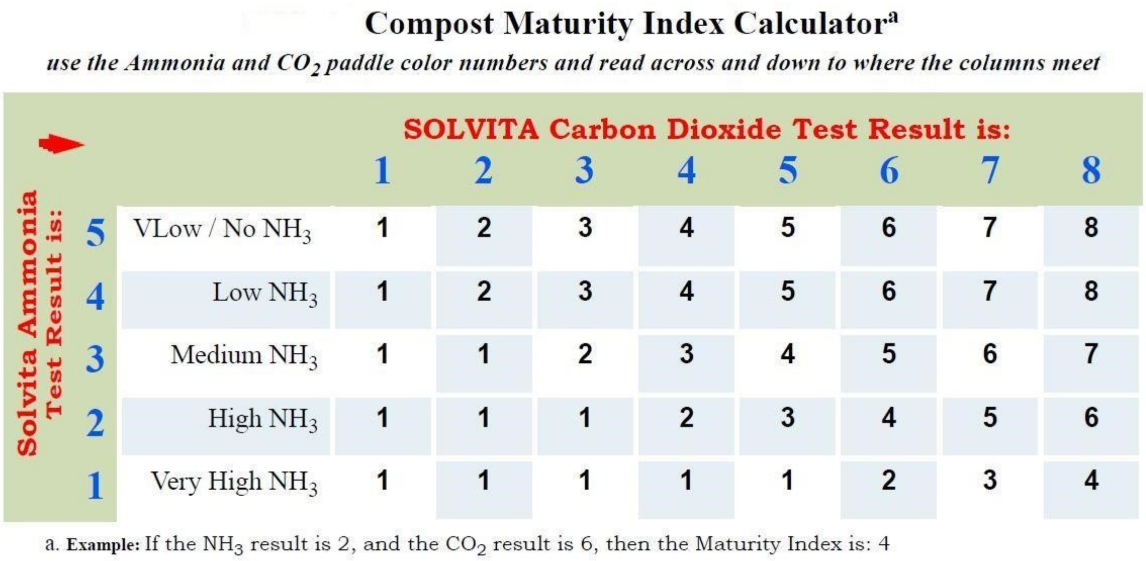
5.4.2 Compost Maturity and Soil Respiration

The Solvita® measurement system developed at the Woods End Laboratories is a rapid method to determine compost maturity and soil health (Woods End Laboratories, 2016). Compost that has not been completely matured can be detrimental to plant growth. The Solvita® compost maturity test provides a simple means of assuring compost will support plant growth when used in biofilters. With this method, compost biological activity is determined by measuring carbon dioxide (CO_2) and ammonia (NH_3) emissions from a sample enclosed in a sealed container. Three replications of the study compost were prepared and tested according to Solvita® compost guidelines (Brinton, 2014). Specially-formulated gel probes placed within the containers react to the concentrations of CO_2 and NH_3 gases, resulting in a color change. After a four-hour period the gel color was read with a digital color reader to determine concentrations of these gases. High concentrations of CO_2 and NH_3 are indicators of immature, unstable compost.

Data for the study compost media are presented in Table 5.11. Comparing this data to the Solvita® guidelines shown in Figures 5.15, 5.16, and 5.17, the compost would have a maturity index of "6." This would put it in the late stages of the curing process trending to mature compost. According to the Solvita® condition guidelines in Figure 5.16, "Solvita 6 and above is commonly recognized as suitable maturity for official uses." This test, in contrast to the poor results from the "Suitability to Grow" test, shows the compost as being mature and suitable for plant growth.

Table 5.11 Solvita® compost maturity test color readings for the study compost media.

Media	Replication	Color (CO_2)	Color (NH_3)
Compost	1	6.75	5
Compost	2	6.61	5
Compost	3	6.65	5



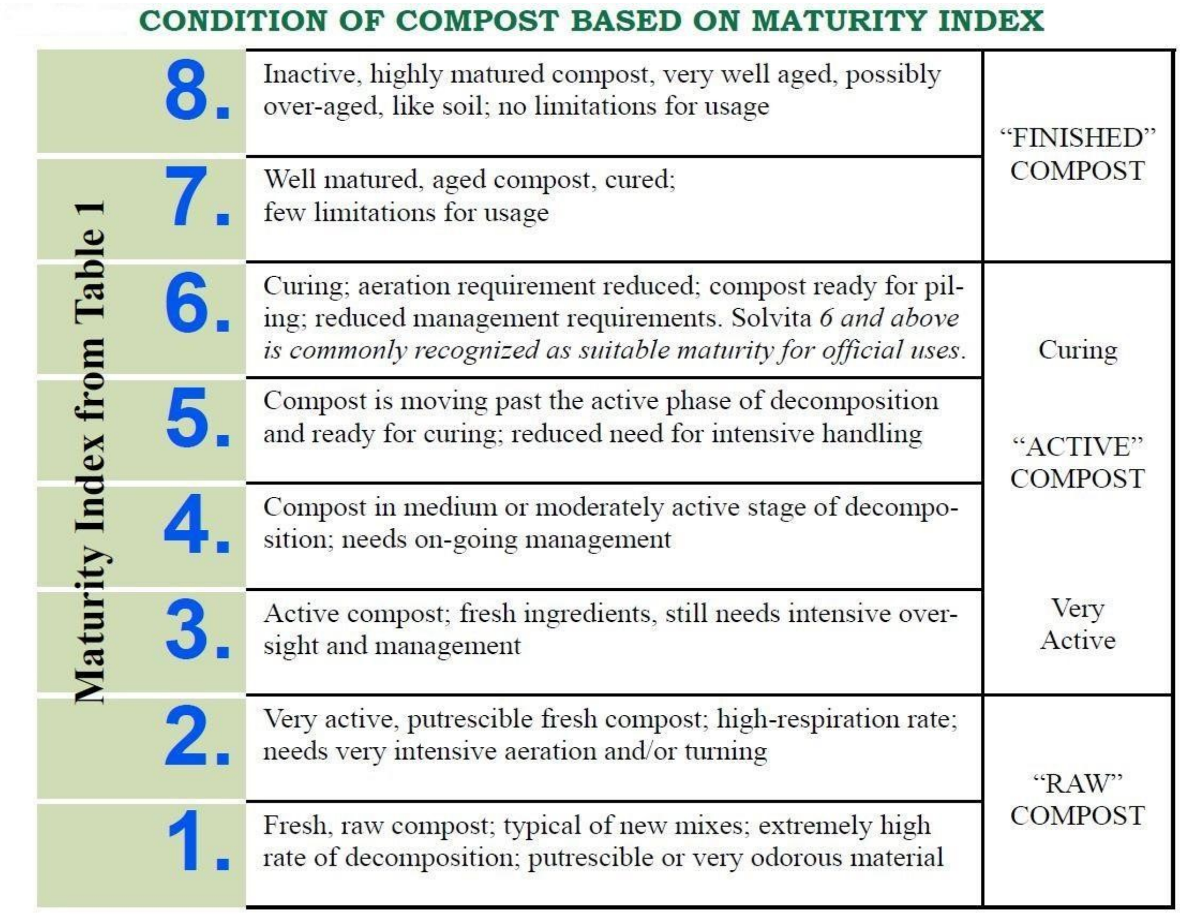
Compost Maturity Index Calculator[a]

use the Ammonia and CO_2 paddle color numbers and read across and down to where the columns meet

Solvita Ammonia Test Result is:		SOLVITA Carbon Dioxide Test Result is: 1	2	3	4	5	6	7	8
5	VLow / No NH_3	1	2	3	4	5	6	7	8
4	Low NH_3	1	2	3	4	5	6	7	8
3	Medium NH_3	1	1	2	3	4	5	6	7
2	High NH_3	1	1	1	2	3	4	5	6
1	Very High NH_3	1	1	1	1	1	2	3	4

a. **Example:** If the NH_3 result is 2, and the CO_2 result is 6, then the Maturity Index is: 4

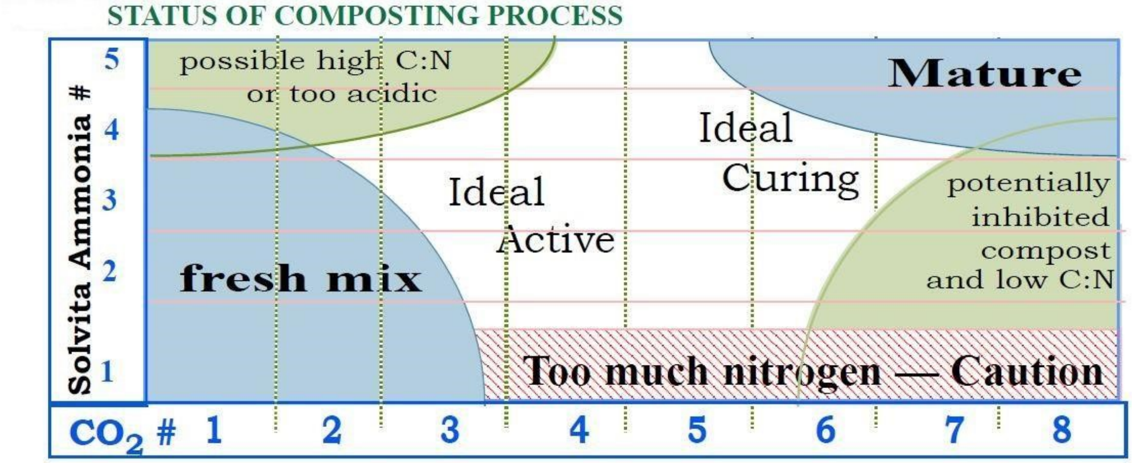
Figure 5.15 Compost Maturity Index Calculator based on Solvita® CO2 and NH3 test results (Brinton, 2014).



CONDITION OF COMPOST BASED ON MATURITY INDEX

Maturity Index from Table 1		
8.	Inactive, highly matured compost, very well aged, possibly over-aged, like soil; no limitations for usage	"FINISHED" COMPOST
7.	Well matured, aged compost, cured; few limitations for usage	
6.	Curing; aeration requirement reduced; compost ready for piling; reduced management requirements. Solvita *6 and above is commonly recognized as suitable maturity for official uses.*	Curing
5.	Compost is moving past the active phase of decomposition and ready for curing; reduced need for intensive handling	"ACTIVE" COMPOST
4.	Compost in medium or moderately active stage of decomposition; needs on-going management	
3.	Active compost; fresh ingredients, still needs intensive oversight and management	Very Active
2.	Very active, putrescible fresh compost; high-respiration rate; needs very intensive aeration and/or turning	"RAW" COMPOST
1.	Fresh, raw compost; typical of new mixes; extremely high rate of decomposition; putrescible or very odorous material	

Figure 5.16 Compost condition based on Solvita® Compost Maturity Index (Brinton, 2014).



Example: If the NH_3 result is 3, and the CO_2 result is 5, then the process is Active moving into Ideal Curing

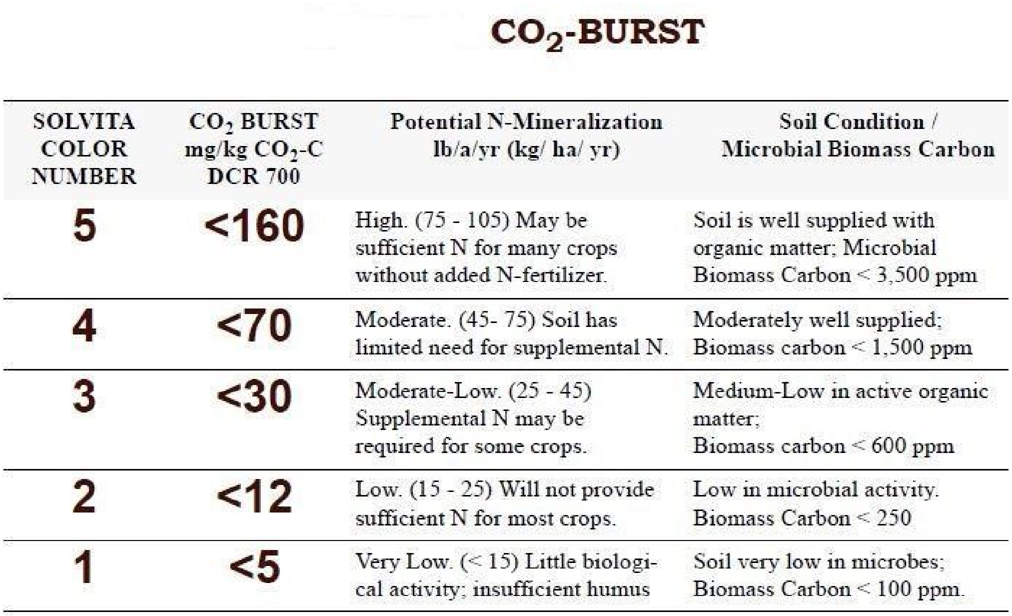
Figure 5.17 Composting process status based on Solvita® CO_2 and NH_3 test results (Brinton, 2014).

The Solvita® system can also be used to determine soil CO_2 and NH_3 respiration. Soil respiration is the evolution of soil CO_2 by microbial activity. Measuring evolved CO_2 using the Solvita® "CO_2-Burst" test can provide an estimate of potential nitrogen (N) mineralization, an indicator of soil health, biological activity, and potential productivity (Brinton, 2013). In addition, the Solvita® "SLAN" (Solvita Labile Amino Nitrogen) test provides a measure of the easily available organic N (Amino-N) that is part of soil humus (Brinton, 2015). Both the Solvita® CO_2-Burst and SLAN tests were performed on the study of peat, muck, sand, and taconite tailings. Three replications of each treatment media were prepared and tested according to Solvita® guidelines (Brinton, 2013; Brinton, 2015) similar to those tests run on compost but with dried soil and a longer 24-hour incubation period. A Solvita® digital color reader was used to determine concentrations of CO_2 and NH_3 gases.

Results for the treatment media are presented in Table 5.12. According to the guidelines in Figures 5.18 and 5.19, peat has a very high potential for N-mineralization—likely sufficient for most crops without additional N-fertilizer—and is unlikely to respond to supplemental nitrogen. Results show that peat is also high in organic matter and soil microbes. Compost is similar to peat with high CO_2 evolution (shown in the compost maturity test) and high Amino-N levels. Results for muck show a high potential for N-mineralization and sufficient organic matter but low Amino-N levels. Muck would likely respond to supplemental N-fertilizer. As expected, sand and tailings both have very low biological activity and soil microbe levels. They are very low in organic matter and have no detectable Amino-N. As such, they will only support sustained plant growth with supplemental organic matter and/or fertilizer.

Table 5.12 Treatment media mean CO_2 and NH_3 concentrations from Solvita® "CO2-Burst" (Brinton, 2013) and "SLAN" tests (Brinton, 2015). n = 3.

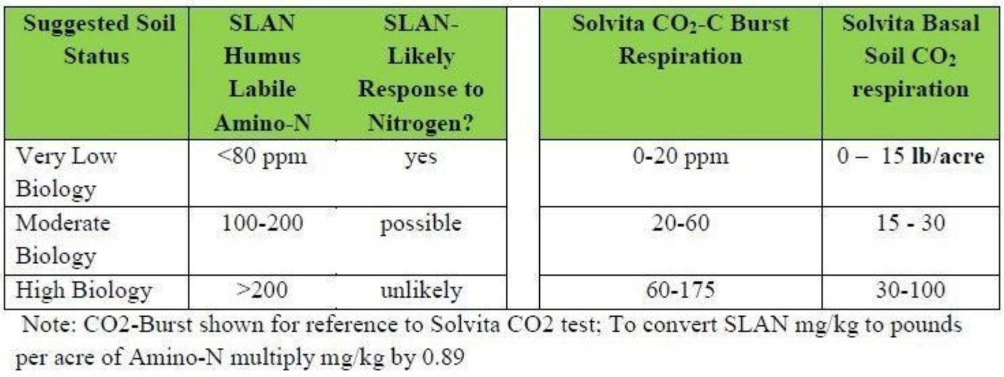
Media	CO_2 (ppm)	Amino-N (ppm)
Peat	850	402.5
Muck	210	75
Compost	-----	445
Sand	2.3	0
Tailings	2.3	0



CO$_2$-BURST

SOLVITA COLOR NUMBER	CO$_2$ BURST mg/kg CO$_2$-C DCR 700	Potential N-Mineralization lb/a/yr (kg/ ha/ yr)	Soil Condition / Microbial Biomass Carbon
5	<160	High. (75 - 105) May be sufficient N for many crops without added N-fertilizer.	Soil is well supplied with organic matter; Microbial Biomass Carbon < 3,500 ppm
4	<70	Moderate. (45- 75) Soil has limited need for supplemental N.	Moderately well supplied; Biomass carbon < 1,500 ppm
3	<30	Moderate-Low. (25 - 45) Supplemental N may be required for some crops.	Medium-Low in active organic matter; Biomass carbon < 600 ppm
2	<12	Low. (15 - 25) Will not provide sufficient N for most crops.	Low in microbial activity. Biomass Carbon < 250
1	<5	Very Low. (< 15) Little biological activity; insufficient humus	Soil very low in microbes; Biomass Carbon < 100 ppm.

Figure 5.18 Potential N-mineralization and soil condition based on Solvita® CO$_2$-Burst test (Brinton, 2013).



Suggested Soil Status	SLAN Humus Labile Amino-N	SLAN-Likely Response to Nitrogen?	Solvita CO$_2$-C Burst Respiration	Solvita Basal Soil CO$_2$ respiration
Very Low Biology	<80 ppm	yes	0-20 ppm	0 – 15 **lb/acre**
Moderate Biology	100-200	possible	20-60	15 - 30
High Biology	>200	unlikely	60-175	30-100

Note: CO2-Burst shown for reference to Solvita CO2 test; To convert SLAN mg/kg to pounds per acre of Amino-N multiply mg/kg by 0.89

Figure 5.19 Soil biological status and likely response to nitrogen based on Solvita® SLAN test (Brinton, 2015).

5.4.3 Seed Germination and Plant Growth

In addition to the MnDOT Suitability to Grow test and Solvita® measurement system, compost, peat, soil media, and substrate mixes were assessed using a plant bioassay that was developed for the evaluation of compost (University of Florida, 2011). The procedure consists of seed germination and plant growth tests that were conducted with both radish and oats in the NRRI greenhouse. Peat, compost, sand, and taconite tailings were tested alone and in various mixtures as detailed in Table 5.13. Muck was not included in the tests due to its heavy clay texture that made it nearly impossible to mix with other materials. Media/mixtures were placed in 7" x 5" x 2" containers and placed in the greenhouse under constant temperature and day length with daily automatic sprinkler watering. For each media/mixture, three replications were planted with six oat seeds and another three replications with six radish seeds. Germination/survival was recorded after seven days. Plants were harvested after 21 days, and whole plant biomass (shoots and roots) dry weights were determined.

Table 5.13 Media/mixture volume ratios used in the germination and plant growth greenhouse trials.

Peat	Compost	Tailings	Sand
100	0	0	0
50	0	50	0
25	0	75	0
10	0	90	0
50	0	0	50
25	0	0	75
10	0	0	90
0	100	0	0
0	50	50	0
0	25	75	0
0	10	90	0
0	50	0	50
0	25	0	75
0	10	0	90
0	0	100	0
0	0	0	100

Germination/survival percent was not significantly different for any of the media/mixtures. Mean dry weights for radish and oats biomass for each media/mixture are presented in Figures 5.20 and 5.21. The data are graphed in descending order. For both radish and oats, the media that resulted in the highest biomass dry weight was the 25% compost – 75% sand mixture (Figure 5.22). This mixture corresponds to the current MnDOT specifications (MnDOT, 2016) for filter media topsoil. It is not clear why the 25% compost – 75% sand mixture performed better than the 25% compost – 75% tailings. One possible explanation could be that the compost-sand mixture inadvertently received more water than the compost-tailings mixture. Photos of the two treatments show more water marks on the identification stakes for the compost-sand mixture. The 25% compost – 75% sand mixture also produced the most oats biomass, followed by the 25% compost – 75% tailings mixture. Both radish and oats containers were in the same flats for each treatment (Figure 5.22). It’s possible that the compost-sand treatment flat received more water, thus resulting in greater biomass for both radish and oats. Further testing of the two treatments should be conducted to confirm or deny this explanation.

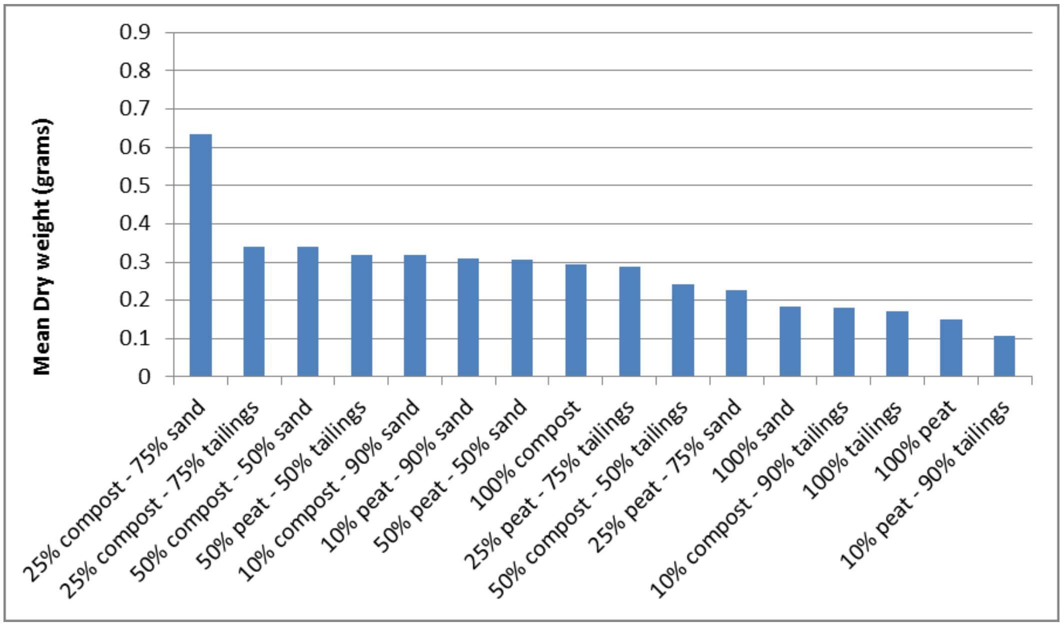


Figure 5.20 Mean dry weight of harvested radish after 21-day growth trial in various treatment media and mixes (n=3).

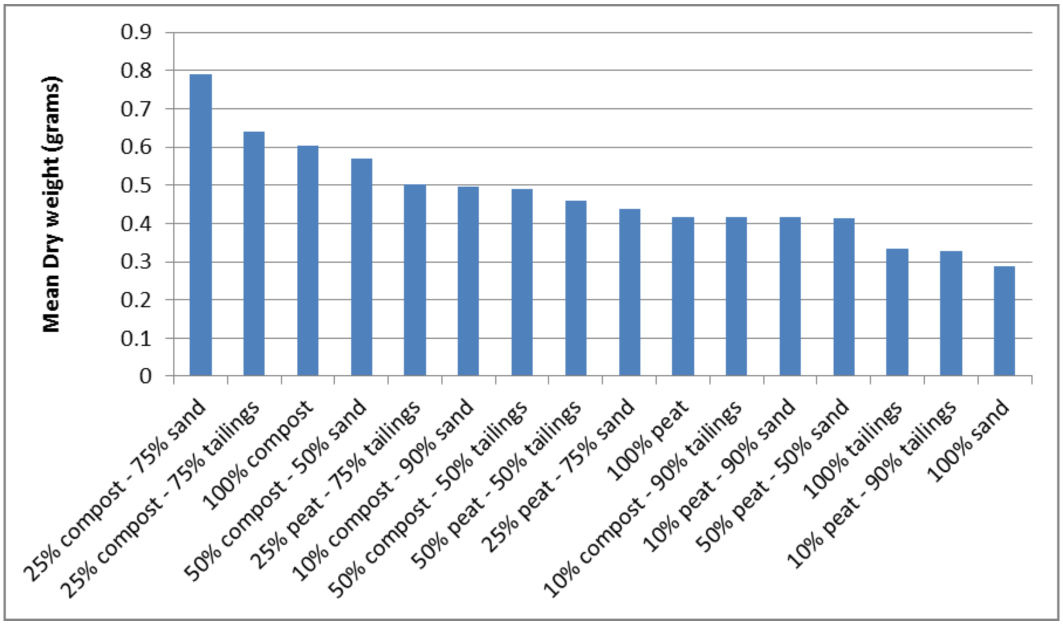


Figure 5.21 Mean dry weight of harvested oats after 21-day growth trial in various treatment media and mixes (n=3).

Figure 5.22 Oats and radish in 25% compost – 75% sand media mixture at 21 days after planting.

5.4.3.1 The effects of peat and compost

Statistical analysis was conducted to determine the effect of peat and compost on germination/survival and biomass dry weight. Survival and dry weights of oats and radish were compared across the percentage of peat or compost used in the media (Figures 5.23 and 5.24). Mean survival and dry weights were compared among the different substrate levels by Tukey HSD test (Table 5.14). Significant difference was found for dry weight of oats, in which media containing compost at 25% by volume produced more dry weight than media with compost at 10% by volume. Media comprised of 50% peat can produce more dry weight for radish than with 100% peat.

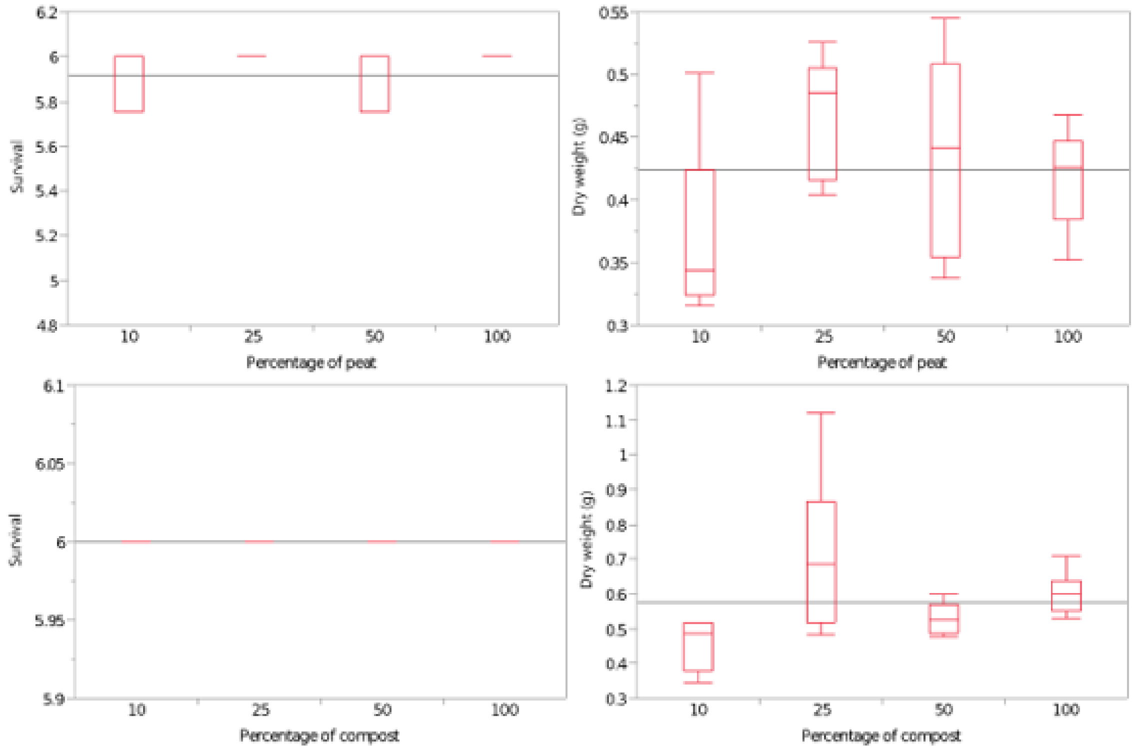


Figure 5.23 Survival and dry weight of oats at different percentages of peat or compost.

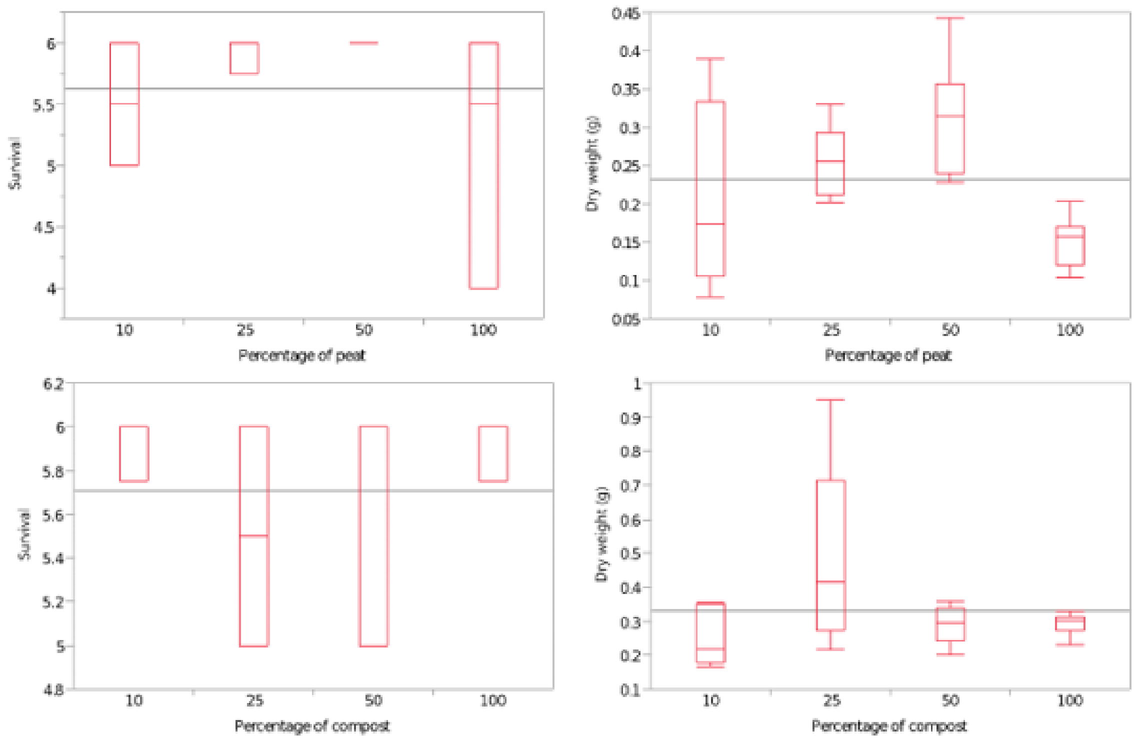


Figure 5.24 Survival and dry weight of radish at different percentages of peat or compost.

Table 5.14 Mean survival and dry weights of oats and radish at different percentages of peat or compost. Numbers with different letters at same column indicates significant difference by Tukey HSD test.

Plant	Substrate	Percentage	Survival	Dry weight
Oats	Peat	10	5.83^A	0.37^A
		25	6^A	0.47^A
		50	5.83^A	0.44^A
		100	6^A	0.42^A
	Compost	10	6^A	0.46^B
		25	6^A	0.72^A
		50	6^A	0.53^{AB}
		100	6^A	0.60^{AB}
Radish	Peat	10	5.5^A	0.21^{AB}
		25	5.83^A	0.26^{AB}
		50	6^A	0.31^A
		100	5.17^A	0.15^B
	Compost	10	5.83^A	0.25^A
		25	5.5^A	0.49^A
		50	5.67^A	0.29^A
		100	5.83^A	0.29^A

The mean values of the difference between compost and peat were compared with zero to examine if significant difference was observed (Table 5.15). For two response variables and two types of plants, only the dry weight of oats presents significant difference from zero (p-value<0.05). The mean was 0.147, which is greater than 0. This positive value indicated that compost produced significantly higher dry weights of oats than peat. For survival or dry weight of radish, there is no significant difference between compost and peat.

Table 5.15 t-test results for the comparison of matched pairs between compost and peat. Significant difference was observed when P-value is less than 0.05.

Plant	Response variable	Mean (compost – peat)	95% confidence interval	P-value (Null hypothesis: Mean of the difference equals to zero)
Oats	Survival	0.095	[-0.055,0.246]	0.1723
	Dry weight	0.147	[0.050,0.244]	**0.0098**
Radish	Survival	0	[-0.398,0.398]	1.000
	Dry weight	0.092	[-0.051,0.235]	0.1665

5.4.3.2 The effects of substrate ratios

Multiple linear regression models using the percent ratio of peat, compost, and tailings as predictors and survival or dry weight as response variable were developed for each plant. During model simulation, the volume percentages of substrates were considered as categorical variables. Model coefficients were summarized in Table 5.16. For survival of oats and radish, no significant model can be developed. Tailings did not affect the dry weight of oats, but tailings significantly reduced the dry weight of radish. Peat and compost improved both plants' growth, particularly when 25% of soil was compost.

Table 5.16 Multiple linear regression model coefficients for survival and dry weights of oats and radish. Significant coefficients (P-value <0.05) were shown in bold. Intercept represents the mean values of survival or dry weight when soil was composed of 25% compost and 75% sand.

	Oats		**Radish**	
	Survival	**Dry weight**	**Survival**	**Dry weight**
(Intercept)	**6.000**	**0.737**	**5.667**	**0.546**
Peat10	0.083	**0.127**	0.000	0.109
Peat25	0.167	**0.205**	0.333	**0.132**
Peat50	-0.083	**0.159**	0.333	**0.150**
Peat100	0.167	**0.131**	-0.500	-0.033
Compost0	-0.167	**-0.450**	0.000	**-0.363**
Compost10	0.083	**-0.238**	0.333	**-0.212**
Compost50	-0.083	**-0.199**	0.000	**-0.235**
Compost100	0.000	**-0.134**	0.167	**-0.253**
Tailings50	0.167	-0.018	0.000	-0.042
Tailings75	0.000	-0.044	-0.333	**-0.117**
Tailings90	-0.167	-0.084	-0.333	**-0.170**
Tailings100	0.167	0.047	0.167	-0.011
Model R^2	0.18	0.70	0.20	0.60
Model P-value	0.58	<0.0001	0.48	<0.0001

5.4.4 Refined greenhouse growth trials

In order to garner more conclusive results than provided by the original greenhouse study on certain aspects of particular interest, a refined study was initiated in April 2017. The goals of the study were to determine the plant growth response to: 1) the effect of sand vs. tailings when used as 75% of the treatment media; and 2) the effect of replacing the remaining 25% of the media with varying amounts of salvaged peat rather than compost.

The study design was similar to the first greenhouse study in that both radish and oats were planted in replicated pots. Media/mixtures were placed in 7" x 5" x 2" containers and placed in the greenhouse under constant temperature and day length with daily automatic sprinkler watering. For each media/mixture, six replications were planted with six oat seeds and another six replications with six radish seeds, as opposed to only three replications in the original greenhouse study. An extra effort was made to completely randomize the pots in flats to ensure no potential effect of unequal watering. The flats were also rearranged each week during the study.

Plants were harvested after 21 days, and whole plant biomass (shoots and roots) dry weights were determined. The dry weight for each replication (six plants combined) was used in the statistical analysis.

Table 5.17 Media/mixture volume ratios used in the revised greenhouse growth trials.

Sand	Tailings	Compost	Peat
75	0	25	0
75	0	15	10
75	0	5	20
0	75	25	0
0	75	15	10
0	75	5	20

5.4.4.1 The effect of sand vs. tailings

Figure 5.25 presents the data distribution of radish and oats weights based on 0% (75% sand) and 75% tailings content for three organic substrate groups: 5% compost+20% peat, 10% compost+15% peat, and 25% compost+0% peat. It should be noted that the inorganic substrate is either 75% sand (labeled 0% tailings) or 75% tailings.

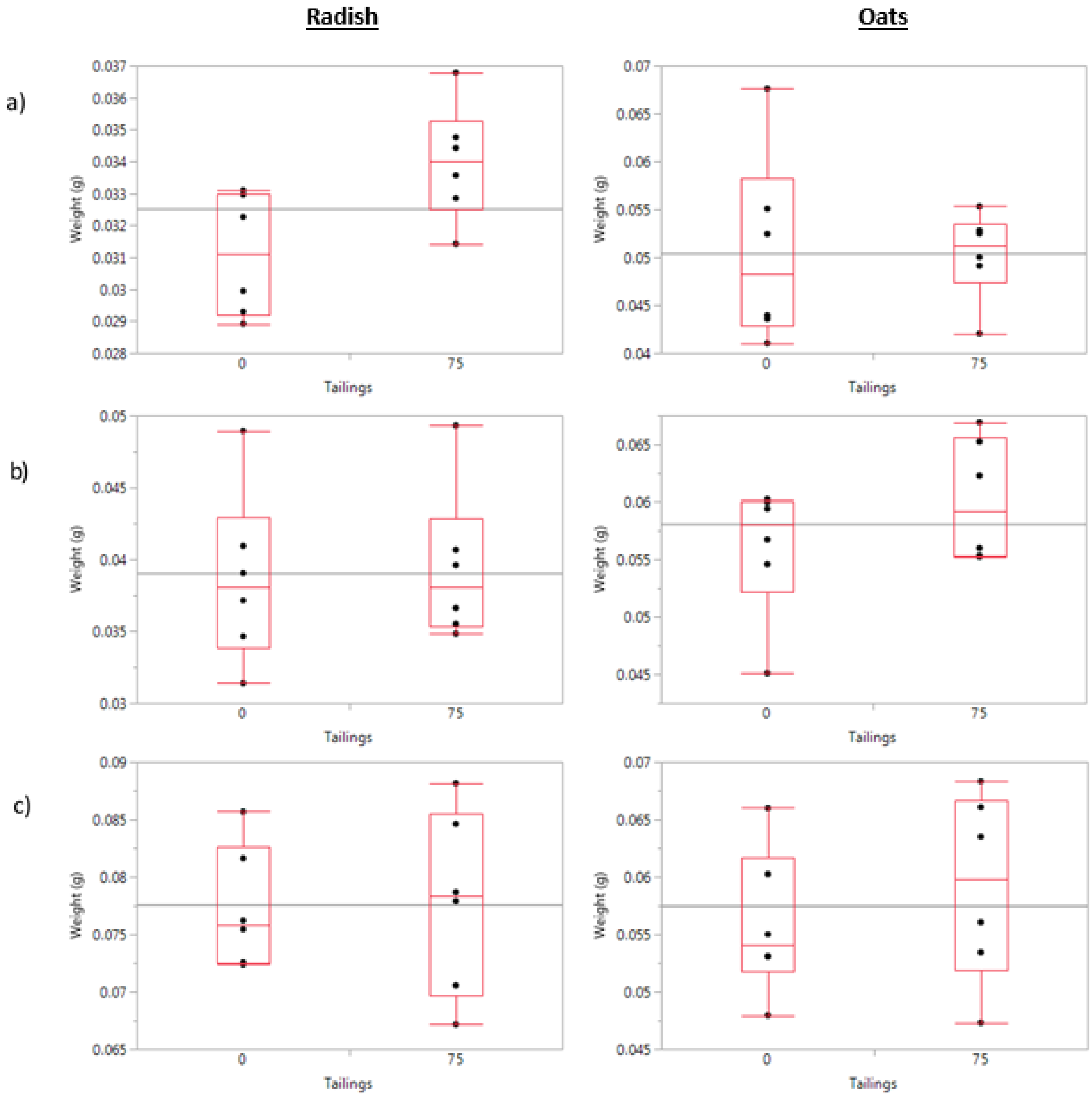


Figure 5.25 Quantile plots of radish (left column) and oats (right column) weights for substrate containing: a) 5% compost+20% peat; b) 10% compost+15% peat; c) 25% compost+0% peat.

Note: The x axis label of 0% tailings is 75% sand.

To test if tailings or sand produce significantly different plant weights, a t-test was performed for plant weights based on tailings composition (0% and 75%) (Table 5.18). In order to take into account the effects caused by different organic material compositions, the test was conducted for each of the three sets of organic compositions (5% compost+20% peat, 10% compost+15% peat, and 25% compost+0% peat). In general, 75% tailings resulted in slightly increased plant weights, but this effect was insignificant except for the 5% compost+20% peat treatment for radishes, where tailings outperformed sand.

Table 5.18 Mean of radish and oat weights were compared by t-test between 0% tailing (in other words 75% sand) and 75% tailing. The significant difference (P-value < 0.05) was in bold for P-value.

Plant	Organic substrate	Mean weight of Radish, g		P-value from t-test
		0% tailing (=75% sand)	75% tailing	
Radish	5% compost+20% peat	0.031	0.034	**0.0231**
	10% compost+15% peat	0.039	0.039	0.8282
	25% compost+0% peat	0.056	0.059	0.4640
Oats	5% compost+20% peat	0.051	0.050	0.9476
	10% compost+15% peat	0.056	0.060	0.2216
	25% compost+0% peat	0.077	0.078	0.8935

5.4.4.2 The effect of replacing compost with peat

As the sand and taconite tailings did not produce a significant difference for most of the studied plant weights, the data from both sand and tailings were combined together to fit a linear regression by using peat/compost ratio as predictor and plant weight as response variable (Figure 5.26). Both radish and oats had a significant decrease in plant weight with increasing peat/compost ratio. These decreasing trends are expressed in Eqs. (5.1) and (5.2) for radish and oats.

$$\text{Radish Weight (g)} = 0.054 - 0.0059 * \text{Peat/compost ratio} \qquad R^2=0.68,\ n=36 \qquad (5.1)$$

$$\text{Oats Weight (g)} = 0.074 - 0.0064 * \text{Peat/compost ratio} \qquad R^2=0.66,\ n=36 \qquad (5.2)$$

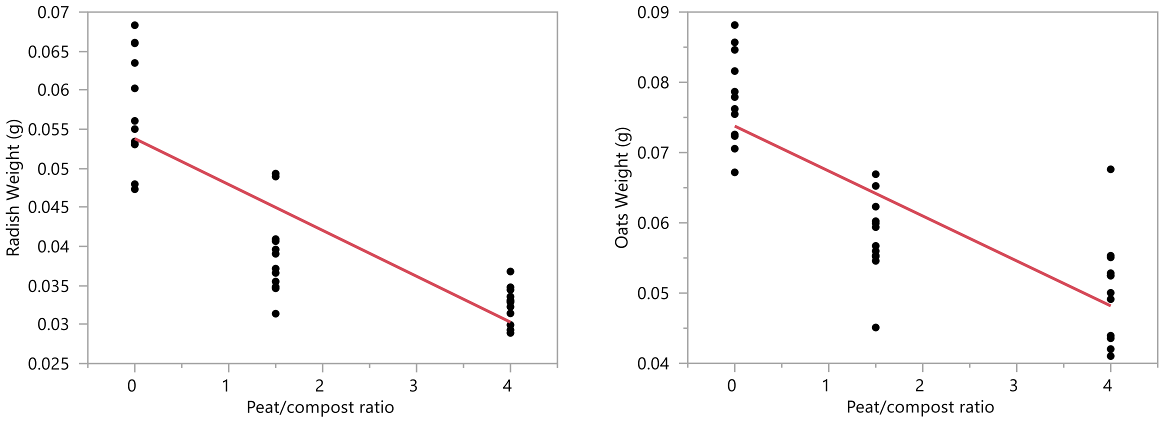


Figure 5.26 The linear fit between plant (radish or oats) weight and peat/compost ratio.

The combined overall effects of sand vs. tailings and replacing compost with peat are shown in Figures 5.27 and 5.28. The results showed little to no significant effect of sand vs. tailings on plant growth response. However, replacing compost with peat resulted in reduced plant growth with increasing amounts of peat. Based on this refined greenhouse study, sand and tailings are interchangeable from a plant growth perspective. Replacing compost with peat, however, may require supplemental fertilizer.

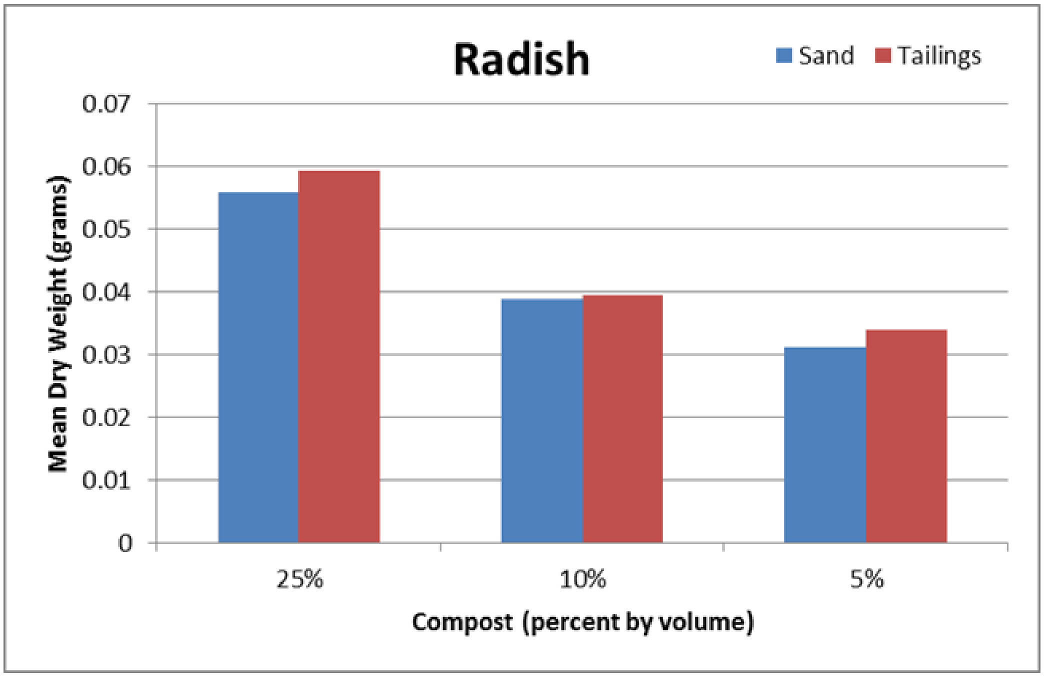


Figure 5.27 Effects of sand vs. tailings and replacing compost with peat on radish mean dry weight in greenhouse studies.

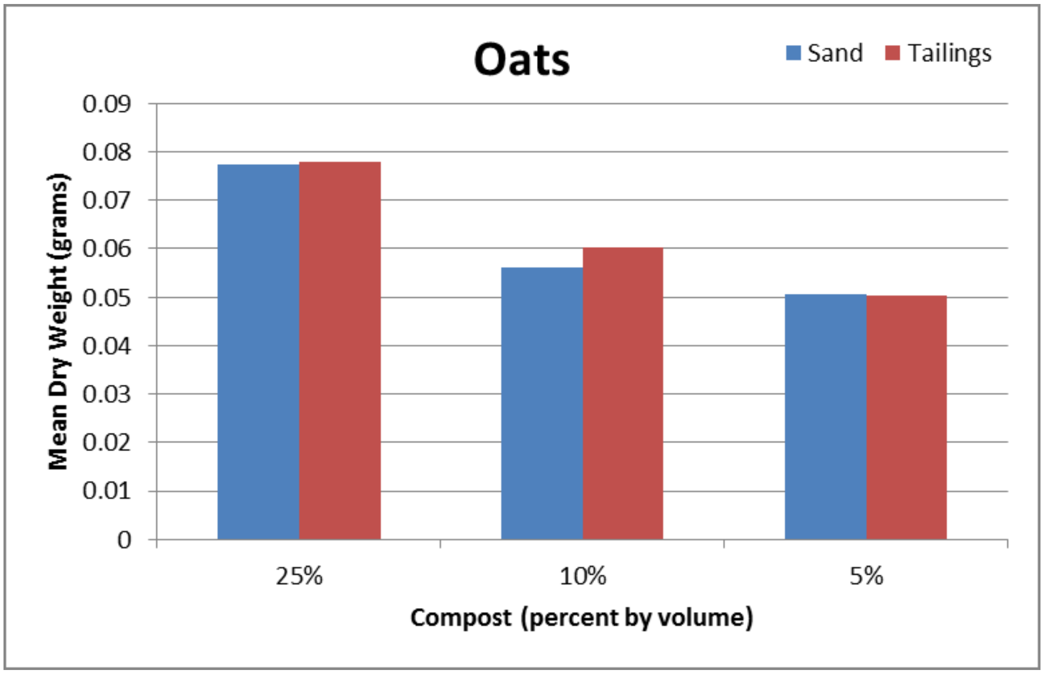


Figure 5.28 Effects of sand vs. tailings and replacing compost with peat on oats mean dry weight in greenhouse studies.

5.4.4.3 Organic component nutrient analyses

To help determine the reasons for the reduced plant growth response with increased replacement of compost with peat, these substrates and muck were analyzed by the University of Minnesota Soils Analytical Laboratory. The substrates were tested according to professional turf management procedures as this most closely approximated the type of growing environment where the substrates would eventually be used. The tests determined macro and micro nutrients, organic matter (O.M), pH, and soluble salts (E.C.). The results are presented in Table 5.19.

Table 5.19 Mean chemical analyses for study peat, compost, and muck (n=3).

Media	O.M. (%)	E.C. (mmhos /cm)	pH	NO_3-N (ppm)	P (ppm)	K (ppm)	SO_4-S (ppm)	Zn (ppm)	Fe (ppm)	Mn (ppm)	Cu (ppm)	B (ppm)	Ca (ppm)	Mg (ppm)
Peat	55.4	0.6	6	60.0	2.3	36.7	22.3	1.2	201.1	12.4	0.4	0.4	3429.0	623.3
Compost	36.3	16.0	7	60.0	100.0	300.0	40.0	33.6	225.2	23.5	5.3	5.0	3572.0	892.3
Muck	8.2	1.9	8	6.4	2.7	97.3	14.7	3.2	95.4	23.2	5.9	0.2	4995.7	514.0

Both peat and compost are high in organic matter and nitrate nitrogen (NO_3-N) and have an optimum pH in the neutral to slightly acidic range. Peat is low in phosphorus (P) and potassium (K), while compost is very high in these macronutrients. This was reflected in lower plant biomass with peat in the greenhouse plant growth trials and suggests that peat would benefit from additional fertilization with these nutrients. The Soil Test Report recommendation calls for 45 lb/acre of phosphate and 90 lb/acre of potash fertilizer.

Soluble salts (E.C. – electrical conductivity) for the study compost considerably exceeded the MnDOT Grade 2 compost requirement of ≤10 mmhos/cm (MnDOT, 2016). This could be the reason for the poor performance of compost in the MnDOT "Suitability to Grow" test. The toxic effect of such high soluble salts was alleviated in the greenhouse growth trials, presumably by dilution with the sand and tailings and by regular watering and leaching. This should be considered when using compost in stormwater treatment media mixes. No supplemental fertilizer should be applied when using compost.

Muck was low in organic matter, NO_3-N and P, with medium levels of K. The pH was quite alkaline at 8. This, combined with its poor physical and handling characteristics, makes it a poor candidate for use in stormwater treatment.

5.4.5 Conclusion

Compost and peat both performed well in mixtures with sand and taconite tailings in providing a viable substrate for plant growth. Media mixes containing compost, especially at 25% compost, performed the best in initial plant growth trials. Muck was difficult to mix with any other media and its value for plant growth minimal. In the initial greenhouse study taconite tailings at higher percentages (>50%) had a negative effect on radish dry weight. In the subsequent refined greenhouse study, results showed little to no significant effect of sand vs. tailings on plant growth response. However, replacing compost with peat resulted in reduced plant growth with increasing amounts of peat. This could perhaps be remedied with additions of supplemental fertilizer. The MnDOT Suitability to Grow test and Solvita® tests provided rapid analysis of potential media and predicted success in the greenhouse trials. The exception was the Suitability to Grow test for compost, which gave false negative results. The seed germination and plant growth greenhouse trials provided the most information on potential treatment media success in supporting plant establishment and growth.

5.5 CONCLUSION

Chapter 5 outlines the results from a testing protocol designed to characterize alternative media for water retention and treatment in bioslopes and bioswales. Material characterizations are summarized by organic group and inorganic group.

5.5.1 Organic group – peat, compost, and muck

Peat materials performed as well or better than compost in all hydraulic, geotechnical, and environmental tests. Peat has a high moisture-holding capacity, hydraulic conductivity, pollutant removal efficiencies, and performs similarly to compost when added as an amendment to sand. Both peat and compost support plant establishment and growth. Mixes containing compost performed the best in plant growth trials. Due to documented variability in peat's properties depending on origin and degree of decomposition, it may be prudent to evaluate peat materials on a case-by-case basis when used in stormwater treatment devices. Supplemental fertilizer containing P and K should be added to peat when soil analysis deems it appropriate.

Muck has deleterious qualities that preclude its recommendation for use in biofilter media mixtures including a low hydraulic conductivity, low workability, relatively low pollutant removal capacities, and a poor plant substrate. The high clay content of the studied muck material impedes infiltration, which may increase the probability of overland flow when used in bioslopes. Additionally, muck material was found to be difficult to mix, adheres to equipment, and when dried becomes hard and impermeable. Due to the high variablity in materials described as "muck," its use in non-infiltration bioslopes and as a topsoil component is highly dependent on the material and application. Although not yet tested as part of this study, muck may be suitable as a topsoil component if amended with sufficient organic matter and gypsum to improve soil structure, supplemental fertilizer, and covered with a mulch to prevent it from drying out. The additional costs incurred with the use of muck would have to be weighed against the savings realized using salvage material.

5.5.2 Inorganic group – taconite tailings and sand

Due to their similar physical characteristics, the hydraulic and geotechnical performance of these materials is similar, making them interchangeable from a civil engineering perspective. In contrast to sand, taconite tailings showed potentials to removal phosphate from water. Sand and tailings are interchangeable from a plant growth perspective.

From laboratory test results, peat was selected as a possible alternative to compost. Pilot tests are underway to compare the infiltration capacity, pollutant removal capability, and fertility of peat mixtures to compost mixtures when subjected to field conditions.

CHAPTER 6: PRELIMINARY FIELD RESULTS AND DISCUSSION

6.1 INTRODUCTION

Chapter 6 provides an overview of treatment system design, media selection, site selection, monitoring methods, and preliminary results from a field pilot test. Media selection for field testing was based on laboratory test results, as described in the previous chapter, which revealed peat as a viable alternative to compost for use in bioslopes and bioswales. The pilot test was designed to assess the performance of peat when used as a soil amendment for improving water retention, water absorption, plant growth, and water quality under field conditions.

6.2 SITE SELECTION

A test area was selected at the NRRI in Hermantown, Minnesota in coordination with the project technical liaison (Figure 6.1). Bioslope test plots were constructed on October 27, 2016 on a 1:5 slope (22% grade) in silty or clayey sand (Figure 6.2).

Figure 6.1 Aerial image of test site located at the NRRI in Hermantown, MN.

Figure 6.2 View of NRRI test site. Study plots are located center right in the image, adjacent to the parking lot.

6.3 PRELIMINARY TREATMENT SYSTEM DESIGN

Mixed media field testing was designed to focus on determining infiltration capacity, pollutant removal, and vegetative support capabilities of the selected filter media mixtures. Media mixtures were blended by volume in accordance with MnDOT Specification 3877.2 to compare a 1:1 mixture of native soil and compost to a 1:1 mixture of native soil and peat. Once media was mixed in proper ratios, six square media beds approximately 36 inches x 36 inches in size (three containing compost and three containing peat) were prepared by placing six inches of treatment media over four inches of gravel. The gravel layer was included to promote drainage via an underdrain (Figure 6.3) to collection vessels (Figure 6.4) which allowed for determination of water quality effects. The plan was to seed the plots with the same seed mix used for the surrounding area. Due to the late installation date and snowfall occurring soon after, this could not be completed in 2016. Native soil samples were collected at the time of construction for laboratory characterization. In addition, instrumentation that monitors rainfall, soil moisture content, temperature and overland runoff (as described in the following section) were installed in the spring of 2017 for long term field monitoring. Plots were seeded in July 2017.

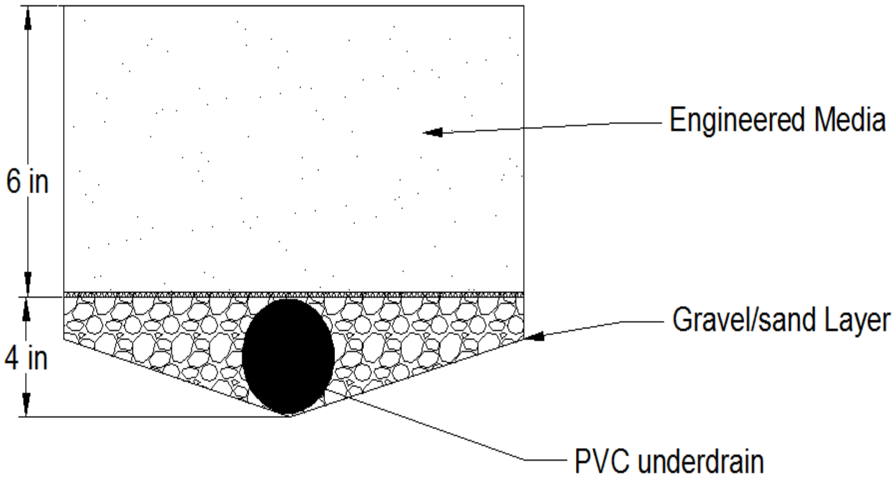


Figure 6.3 Cross section of mixed media pilot plant.

Figure 6.4 Effluent water collection vessel for water quality analysis.

6.4 MONITORING METHOD AND EQUIPMENT

Field monitoring instrumentation was designed and installed to monitor rainfall, soil-moisture content, and temperature. All HOBO® brand instruments, software, and data loggers used for field monitoring were purchased from Onset Computer Corporation. The objective of the monitoring equipment was to compare the infiltration capacity performance of compost and peat when added as a soil amendment to native soils. By monitoring rainfall and soil moisture, a water balance was calculated to determine the amount of water captured by the pilot plots. Temperature data was included to gain knowledge on conditions during which surface runoff was observed, for example, when soil is frozen. Frozen ground conditions were deemed possible during spring and fall, when rainfall and freezing temperatures are likely to be concurrent.

The instruments used include a data logger (Figure 6.5) with 10 ports to accommodate six soil moisture sensors (Figure 6.6), a rain gauge (Figure 6.7), and a temperature sensor (Figure 6.8). A solar panel (Figure 6.9) was installed to provide a trickle charge for the 10 Amp hour battery to extend battery life.

Figure 6.5 Multi-channel data logger for data storage.

Figure 6.6 Soil moisture probe.

Figure 6.7 Rain gauge.

Figure 6.8 Temperature sensor.

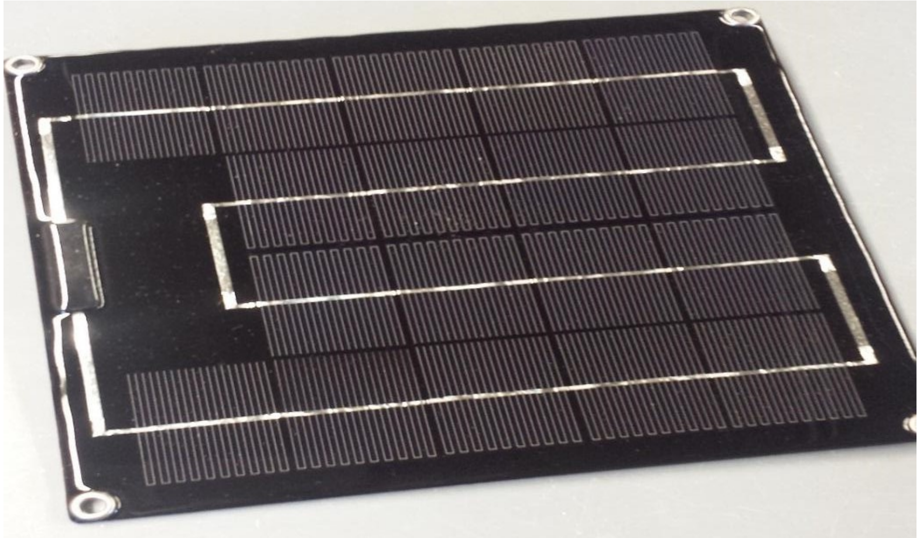


Figure 6.9 Solar panel for providing trickle charge of data logger.

6.5 RESULTS

This section describes the preliminary results from the *in situ* testing program outlined in the previous section. *In situ* monitoring and collection focused on vegetative growth, water-holding capacity, and filtration of biofilter media. This section covers preliminary results from measurements taken in the spring and summer of 2017 in each of the three major areas of interest to this project: infiltration capacity, water quality, and vegetative support.

6.5.1 INFILTRATION CAPACITY

The infiltration capacity of six mixed biofilter media plots was tested in the field during the months of April and May 2017. Three plots contained equal mixtures of MnDOT Grade 2 compost and native soil (silty or clayey sand) and three plots contained an equal mixture of peat and native soil. The field plots were monitored for soil moisture content and rainfall data to estimate and compare water absorption. Peat and compost amendments to native soils resulted in similar water absorbing capabilities, shown in Table 6.1 and Figure 6.10.

Table 6.1 Comparison of water absorbing capacity of peat and compost biofilter media plots.

Rainfall event	Media Type	Pre-Event Moisture Content (%)	Peak-Event Moisture Content (%)	Average Water Absorption (%)
4/18 – 4/20	Peat	28	40	12
		24	36	
		24	35	
	Compost	21	33	11
		26	35	
		20	32	
4/23 – 4/26	Peat	28	37	10
		24	35	
		21	31	
	Compost	21	31	10
		26	35	
		22	31	
4/28	Peat	28	31	9
		24	35	
		21	34	
	Compost	20	31	10
		26	35	
		22	31	
5/1 – 5/3	Peat	31	32	1
		29	30	
		28	29	
	Compost	27	28	1
		30	31	
		26	27	

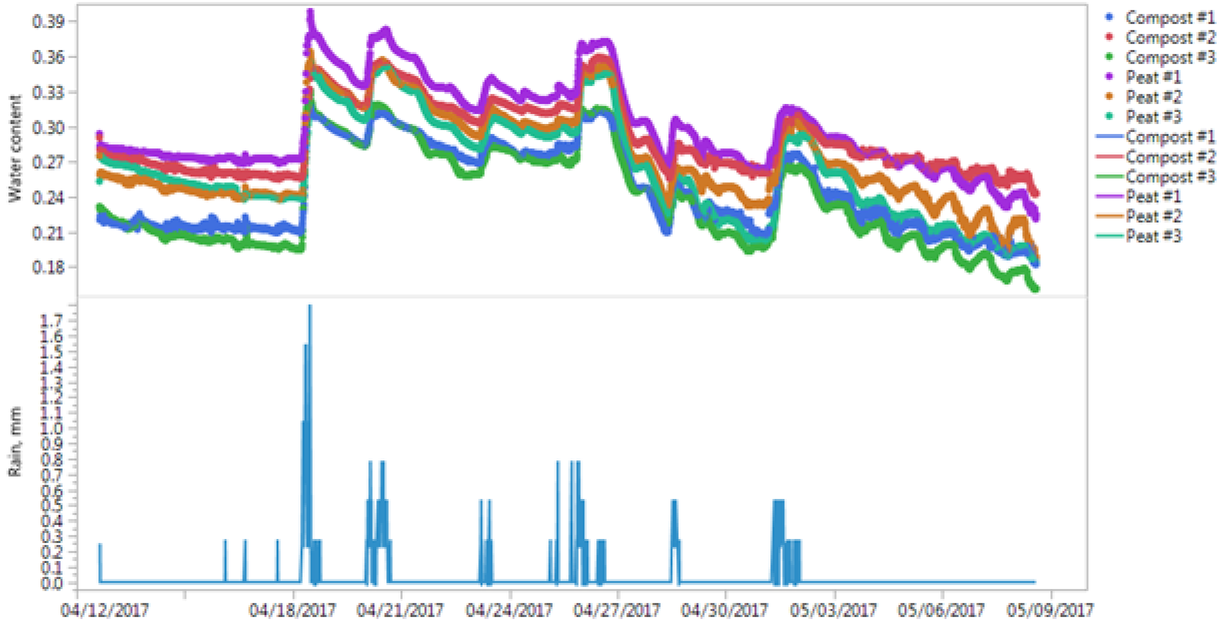


Figure 6.10 Preliminary data comparing rainfall events to *in situ* water content in peat and compost biofilter media plots.

6.5.2 WATER QUALITY

Samples from twelve rain events (Figure 6.11) were collected between the end of October 2016 (the site constructed) and the middle of August 2017. The rain events on April 19 and April 21 were close to each other; therefore, samples from these two events were combined together.

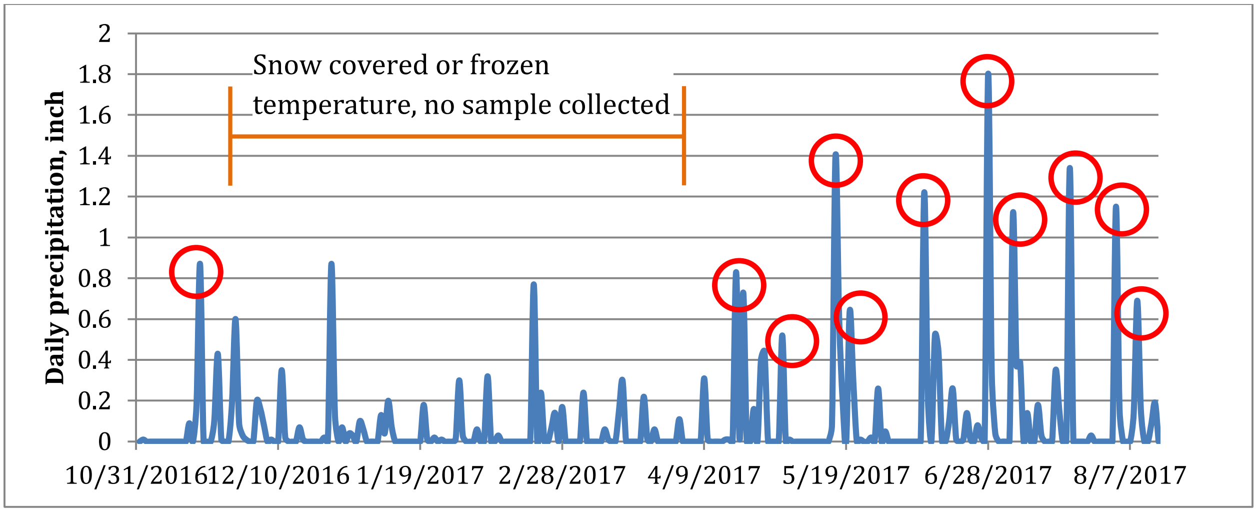


Figure 6.11 Daily precipitation record between November 1, 2016 and August 15, 2017 for the weather station located at the Duluth Airport, which is about 1000 ft. distance to project field plot. Red circle gives the rain events that have water samples collected. Precipitation data were downloaded from NOAA (2017).

For each rain event, samples from rainwater, compost plots, and peat plots were collected. Initially we designed three compost plots and three peat plots to get average data for compost and peat plots. Unfortunately, only two of three compost plots and two peat plots had filtrated water collected, probably due to potential leaking pipes in the other three plots.

Samples were analyzed for pH, metals (Cu, Pb and Zn), and phosphate in the laboratory (Figure 6.12). Lead concentrations were below the detection limit (1 µg/L) for most samples and are therefore not reported here. In general, chemical concentrations ranked from high to low were compost effluent, peat effluent, and rainwater. Rain water was slightly acidic to neutral, while effluents from compost and peat were neutral. Both compost and peat released copper slightly, less than 100 µg/L. However, a large amount of zinc (maximum concentration = 433 µg/L) was leached from compost when zinc concentration in rainwater and peat effluent were below 25 µg/L and below 150 µg/L, respectively. Similar to previous laboratory column leaching experiment results, the field study also showed the export of a large amount of phosphate, ranging from 373 to 11 656 µg/L, from compost plots. Peat discharged phosphate to water, too, but at relatively small amount (below 210 µg/L).

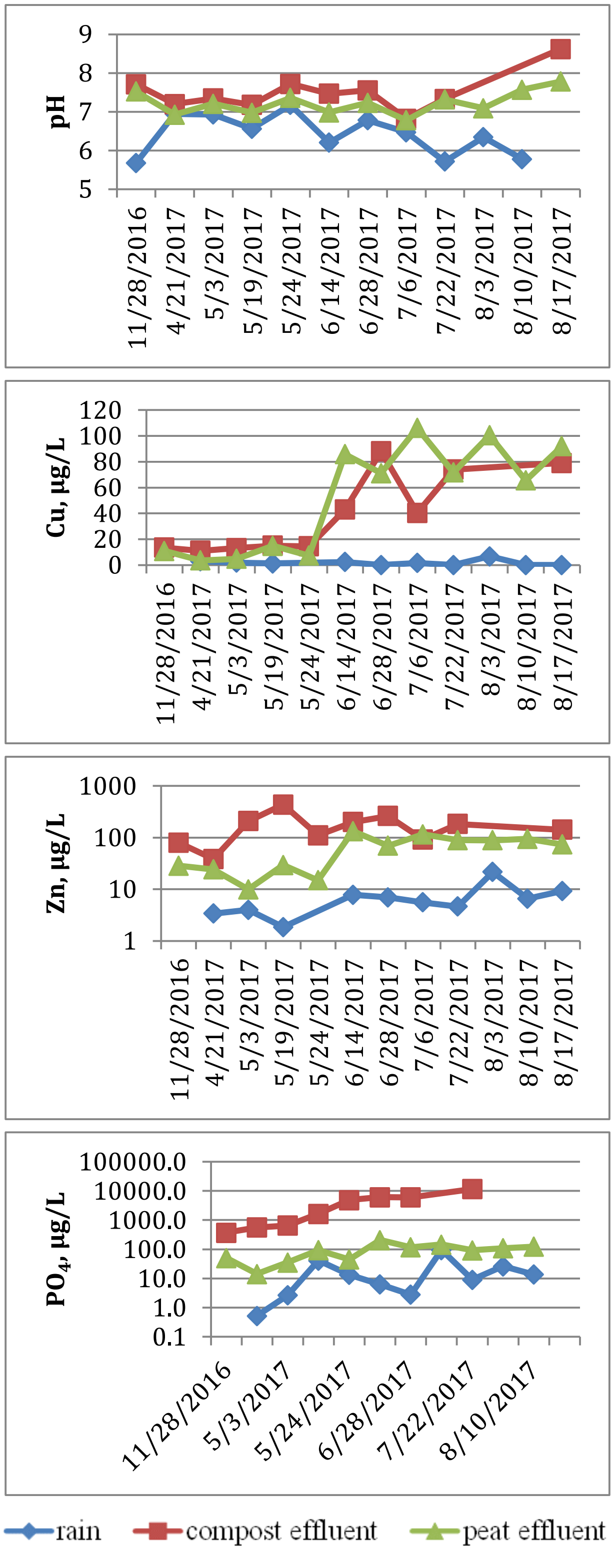
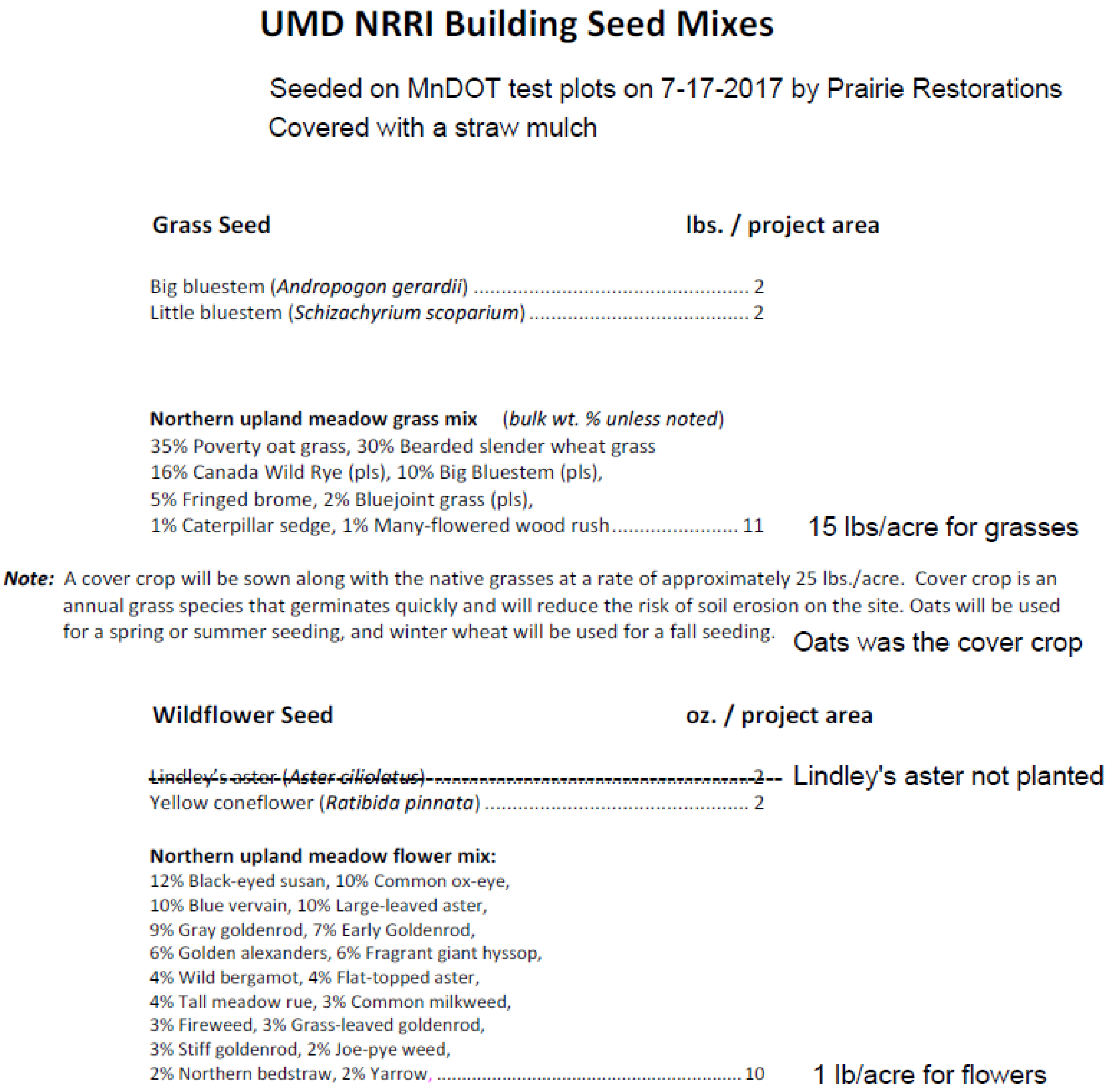


Figure 6.12 pH and the concentrations of copper (Cu), zinc (Zn), and phosphate in rain water and effluent from compost and peat plots collected in 12 rain events.

6.5.3 VEGETATIVE SUPPORT

Due to the late fall study installation date and snowfall, the plots were not seeded in the fall of 2016. However, some weedy vegetation had established on the plots during the 2017 spring season. Photos of the plots were taken on June 12, 2017. As seen in Figure 6.13, the plots containing the compost mixture had considerably more vegetative cover than the plots containing the peat mixture. The plots were cleared of all weedy vegetation in preparation for seeding that occurred on July 17, 2017. All plots were seeded with the same seed mix (Figure 6.14) as used on the rest of the study slope location and covered with a straw mulch. Photos taken on July 26 (Figure 6.15) and August 9, 2017 (Figure 6.16) show good growth of the oats cover crop on both compost and peat substrates.

Figure 6.13 Vegetation on compost (top) and peat (bottom) plots. Photographed on June 12, 2017.



UMD NRRI Building Seed Mixes

Seeded on MnDOT test plots on 7-17-2017 by Prairie Restorations
Covered with a straw mulch

Grass Seed	**lbs. / project area**	
Big bluestem (*Andropogon gerardii*)	2	
Little bluestem (*Schizachyrium scoparium*)	2	
Northern upland meadow grass mix (*bulk wt. % unless noted*) 35% Poverty oat grass, 30% Bearded slender wheat grass 16% Canada Wild Rye (pls), 10% Big Bluestem (pls), 5% Fringed brome, 2% Bluejoint grass (pls), 1% Caterpillar sedge, 1% Many-flowered wood rush	11	15 lbs/acre for grasses

Note: A cover crop will be sown along with the native grasses at a rate of approximately 25 lbs./acre. Cover crop is an annual grass species that germinates quickly and will reduce the risk of soil erosion on the site. Oats will be used for a spring or summer seeding, and winter wheat will be used for a fall seeding. Oats was the cover crop

Wildflower Seed	**oz. / project area**	
~~Lindley's aster (*Aster ciliolatus*)~~	~~2~~--	Lindley's aster not planted
Yellow coneflower (*Ratibida pinnata*)	2	
Northern upland meadow flower mix: 12% Black-eyed susan, 10% Common ox-eye, 10% Blue vervain, 10% Large-leaved aster, 9% Gray goldenrod, 7% Early Goldenrod, 6% Golden alexanders, 6% Fragrant giant hyssop, 4% Wild bergamot, 4% Flat-topped aster, 4% Tall meadow rue, 3% Common milkweed, 3% Fireweed, 3% Grass-leaved goldenrod, 3% Stiff goldenrod, 2% Joe-pye weed, 2% Northern bedstraw, 2% Yarrow,	10	1 lb/acre for flowers

Figure 6.14 Seed mix planted on NRRI MnDOT research plots on July 17, 2017.

Figure 6.15 Vegetation on compost (top) and peat (bottom) plots. Photographed on July 26, 2017.

Figure 6.16 Vegetation on compost (top) and peat (bottom) plots. Photographed on August 9, 2017.

Vegetation monitoring will continue throughout the summer. Photographs of each plot will be continued for an overall qualitative assessment. The plots will also be surveyed using a “Cover-Point Optical Device” (Figure 6.17). The Cover-Point Optical Device (ESCO Associates Inc., Boulder, Colorado) is designed for use in determining percent vegetative cover using the point-intercept method. The system consists of an optical device mounted on a horizontal bar that is supported above the sampling area on one end by a standard photographic tripod and on the other by an adjustable support rod. The optical device, similar in appearance to a telescopic rifle sight, has 5X magnification with extremely fine cross hairs for viewing a relatively dimensionless point. The horizontal bar is approximately one meter long with 10 stops at 10 cm intervals. The percent vegetative cover is determined by looking through the eyepiece and recording hits and misses of vegetation using the fine cross hairs within the optics for each of 10 sample points across the bar. Several such transects were conducted for each plot to determine percent vegetative cover. The point-intercept method will give a repeatable quantitative estimate of the ability of the various biofilter mixes to support plant growth.

Figure 6.17 Cover-Point Optical Device used to determine percent plant cover.

Initial photographs of weed growth prior to seeding show significantly better qualitative plant growth on the compost plots. After seeding, this qualitative difference is less pronounced. Quantitative measurement of the plots using the Cover-Point Optical Device was conducted on August 11, 2017. Three transects for a total of 30 points were recorded as vegetated or not vegetated for each plot. The results are shown in Table 6.2. Mean percent cover for the compost plots was 31% and 43% for the peat plots. Plant cover at this time was primarily oats, the cover crop included with the seed mix. The other seed mix native plant species are expected to establish over time.

Table 6.2. Percent cover for NRRI MnDOT biofilter research plots determined on August 11, 2017 using a Cover-Point Optical Device (n=30).

	Percent Cover	Mean
Compost 1	20%	31%
Compost 2	43%	
Compost 3	30%	
Peat 1	47%	43%
Peat 2	60%	
Peat 3	23%	

CHAPTER 7: CONCLUSION

7.1 PROJECT CONCLUSIONS

This project demonstrated that peat has a high potential to replace commercial compost in MnDOT standard bioslope and bioswale design. Additionally, taconite tailings performed in a comparable fashion as the sand currently specified in MnDOT designs. Results from this project showed that muck has little potential to replace commercial compost or peat due to low permeability and infiltration capacity, filtration, and plant growth support. Finally, a pilot field study established good agreement between laboratory results and field measurements for the 50:50 peat-sand mixes as well as comparing performance between peat-sand mixes and compost-sand mixes.

Finding alternatives to commercial compost and sand would help MnDOT meet regulatory requirements as well as reduce purchase and shipping costs and the need to transport and store excavated material from rural road construction sites. This project exhibits the potential to use what was previously waste material in a beneficial manner.

7.2 CIVIL ENGINEERING CONCLUSIONS

The primary civil engineering design requirement was infiltration rate. Because the saturated condition represents the worst-case scenario, saturated hydraulic conductivity was used as a measure of infiltration rate and, therefore, water-holding capacity. A minimum requirement of 1.5*10-4 cm/sec was determined from testing current MnDOT requirements for bioslope and bioswale design (40 – 60% commercial compost mixed with sand). Laboratory results showed that muck had unacceptably low hydraulic conductivity. Peat performed at least as well as compost in terms of saturated hydraulic conductivity and other important hydraulic and geotechnical considerations. Additionally, taconite tailings and sand were interchangeable from a civil engineering perspective. A pilot field study comparing a 50:50 mix of peat and sand with the same percentage mix of compost and sand was installed. Initial data showed the two mixes had similar water storage capacity.

Due to the variability of materials, not all peat or taconite tailing will behave the same. Results from this project show that the saturated infiltration rate as measured using the falling head test best predicts a biofilter media mixture’s ability to meet civil engineering requirements. In summary, mixtures composed of 40 – 60% peat with the remainder composed of either sand or taconite tailings compare favorably with current MnDOT specifications for bioslope and bioswale design.

7.3 ENVIRONMENTAL ENGINEERING CONCLUSIONS

The environmental tests of salvaged filtration materials quantified pollution retention capacities of each material under steady or dynamic conditions. Under steady conditions, salvaged peat, compost, and commercial peat had high metal (copper, lead, and zinc) retention capacities, generally over 80%, and the difference among these materials was small. Muck can adsorb around 50% of metals. In contrast to the high removal efficiencies for metals, these organic materials did not remove nutrients, especially compost, which released a significant amount of nitrate and some phosphate.

The export of phosphate from compost was also observed in column leaching experiments and the field pilot test. More than 1 000 µg/L phosphate was exported from compost columns or field pilots containing compost. In addition, average compost metal removal efficiencies were around 83% for copper and zinc, which were significantly lower than salvaged peat metal removal efficiencies of more than 98% under dynamic conditions.

Taconite tailings showed potential to remove phosphate, especially under slightly acidic conditions (pH around 6). Commercial peat produced acidic outflow, and the combination of commercial peat with taconite tailings resulted in outflow phosphate concentrations of around 10 µg/L.

Overall, salvaged peat had better pollutant remove efficiencies than compost. Taconite tailings can be used to replace sand and to enhance potential phosphate removal.

7.4 BIOLOGICAL CONCLUSIONS

Compost and peat both performed well in mixtures with sand and taconite tailings in providing a viable substrate for plant growth. Media mixes containing compost, especially at 25% compost, performed the best in plant growth trials. Muck was difficult to mix with any other media, and its value for plant growth was minimal. Greenhouse study results showed little to no significant effect of sand vs. tailings on plant growth response. However, replacing compost with peat resulted in reduced plant growth with increasing amounts of peat. This could be remedied with additions of supplemental phosphorus and potassium fertilizer as these were shown to be deficient in the nutrient analyses.

The MnDOT Suitability to Grow test and Solvita® tests have the potential for rapid analysis of media, and in most cases, predicted success in the greenhouse trials. The exception was the Suitability to Grow test for compost, which gave false negative results. The seed germination and plant growth greenhouse trials, and nutrient analysis provided the most information on potential treatment media success in supporting plant establishment and growth.

Both peat and compost support plant establishment and growth. Due to documented variability in peat's properties, depending on origin and degree of decomposition, it may be prudent to evaluate peat materials on a case-by-case basis when used in stormwater treatment devices. Sand and taconite tailings are interchangeable from a plant growth perspective.

7.5 POTENTIAL FOR FUTURE RESEARCH

This project primarily focused on the laboratory assessment of biofiltration media mixtures. A pilot field study began in the spring of 2017. Initial results from the field study showed good agreement with laboratory results in each of the three areas of the project. However, several factors were not considered in the pilot field project including performance with time after installation and variability of material. Accordingly, the authors and technical advisor on this project are interested in studying field performance of biofiltration media mixtures in more detail.

A follow-on project beginning in the fall of 2017 will continue to monitor the pilot field study area. Additionally, a large-scale biofiltration system based on recommendations from this project is planned for an existing MnDOT construction project. This system will be instrumented and monitored through time, at least through the end of the follow-on project (summer 2019). Finally, previously constructed biofiltration systems will be instrumented and monitored. Results from these systems will give an indication of performance through time after construction.

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