Trees and Structural Soil as a Stormwater Management System in Urban Settings

by

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(Abstract)

Urban runoff continues to impair water quality and there is an increasing need for stormwater management within the limited confines of urban spaces. We propose a system of structural soil and trees that can be incorporated beneath pavement. Structural soil has a high load-bearing capacity yet is engineered to support tree root growth. Stormwater is directed into a structural soil reservoir below the pavement where tree roots can also thrive.

Two container experiments evaluated tree function in this system. We examined whether tree roots can grow into compacted subsoils and if root penetration increases soil infiltration rate. *Quercus* v*elutina, Acer rubrum,* and a no-tree variant were planted in 26.5 L (7 gal) containers and the rootballs surrounded by compacted clay loam. Roots grew into all layers of the compacted soil. Infiltration rate increased by 63% (+/-2%) compared to no-tree containers. A second experiment evaluated water uptake and tree development in fluctuating water tables. *Quercus bicolor* and *Fraxinus pennsylvanica* were planted in 94.6 L (25 gal) containers with structural soils (either Stalite or CU® Structural Soil). Trees were subjected to fluctuating water tables simulating infiltration rates of 2, 1, and 0.1 cm/hr for two growing seasons.

Trees thrived in all infiltration regimes but roots were shallower in slowly drained treatments. Trees grew best and transpired the highest water volume with moderate infiltration. Even if trees uptake only small volumes of water, increased canopy size compared to conventional plantings (because of greater penetrable soil volume) allows greater rainfall interception thus decreasing runoff.

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Dedication

to
my mom, Susan Day, and Roger Harris
for their unfailing support

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Chapter 1: Introduction and Literature Review

Urban runoff often contains a great amount of pollutants, such as sediments, oxygen-demanding substances (organic matter), nutrients (phosphorus, nitrogen), toxic substances, and bacteria (Dennison, 1996b). Consequences of water pollution caused by runoff are destroyed habitat, unsafe drinking water, fish kills, and beach closure (EPA, 2004c). Urbanization also leads to more impervious surface, such as streets and buildings, causing greatly reduced water infiltration into the ground and a subsequent decrease in groundwater recharge (Pitt et al., 1994), which leads to less available water for base flow between storms. As a result, urban streams are flashy, i.e. running higher and faster during storms but often becoming dry between them (Randolph, 2004a). On-site stormwater management would decrease the amount of runoff and thus pollution of water bodies and it could, depending on the system, recharge groundwater. Many common stormwater management facilities (SWMF) require a large area, such as detention ponds. Others are made for ultra-urban areas and take up very little space, but don't provide groundwater recharge. There is therefore a need for research that develops more suitable solutions for urban settings. This thesis describes experiments using structural soil and trees as a storm water management system that can be combined with common urban construction elements, such as streets and parking lots, resulting in no additional above-ground space allocated for stormwater storage.

Overview of the Urban Stormwater Management Problem

Pollution and the effect of urban runoff

Water quality conditions in the United States continue to deteriorate. The Environmental Protection Agency (EPA) assessed 19% (~1,100,000 km^2, 424,712.4 miles^2) of U.S. water bodies in 2000 and reported that 39% of the rivers, 45% of the lakes, and 51% of estuaries are impaired. The main stressors are pathogens, sediments, nutrients, metals (primarily mercury) and pesticides (EPA, 2002b; EPA, 2002c; EPA, 2004c), toxic chemicals, grease (EPA, 2004a), salts, and oils (EPA, 2004c). Sheetflow from sidewalks can contain greatly increased amounts of bacteria, and viruses are commonly found in groundwater close to stormwater recharge basins. Table 1.1 shows examples of toxicant concentrations and likely sources and locations (Pitt et al., 1994):

Table 1.1) Toxicant concentrations and source and location in urbanized areas (Burton and Pitt, 2002; EPA, 1999; Pitt et al., 1994; Pitt et al., 1995)

Toxicant	Max. Concentration (μg/L)	Source / Location
Cadmium	220	vehicle service area runoff / street runoff
Copper	1250	urban received water / street water
Pyrene	102	oils, gasoline
Naphthalene	296	gasoline, insecticides, coal tar
Zinc	650; 135	parking areas; residential areas
Total Phosphorus	383	atmosphere, roadside fertilizer application / residential areas
Nitrate + Nitrite	736	atmosphere, roadside fertilizer application / residential areas
Total Suspended Sediments	101,000	parking areas / residential areas
Total Lead	144	residential areas
BOD*	10,000	residential areas
COD**	73,000	residential areas

*BOD: biochemical oxygen demand
**COD: chemical oxygen demand

Cadmium is a toxic metal, even in low concentrations, and it accumulates in organisms and ecosystems. Although copper is essential in all higher plants and animals, all copper compounds are generally treated as toxic, unless otherwise known. The LD50 for copper sulfate is 30 mg/kg (0.48 oz/lb), meaning just a few grams can be fatal to humans. It is also very toxic to aquatic life; even at recommended rates, copper sulfate can be poisonous to trout and other fish (EXTOXNET, 1994). Animal studies have shown that pyrene, which is commercially used in dyes, pesticides, and plastics, is toxic to the liver and kidney (EPA, 2006). Large amounts of naphthalene, used as a chemical intermediate to produce other chemicals, can destroy red blood cells (hemolytic anemia) causing nausea, vomiting, diarrhea, and blood in the urine (EPA, 2000). This indicates that toxicants can have a great effect on human and wildlife health and that the source and location of these toxicants need continuing or even enhanced management to decrease the amounts and improve environmental conditions. Preventing runoff from reaching water bodies by allowing it to infiltrate may allow natural decontamination by soil-borne microorganisms of the toxicants.

Besides runoff from agricultural areas, which is the main source of runoff impairing water bodies, urban runoff is among the top four sources for pollution of rivers, lakes, and estuaries (EPA, 2002b; EPA, 2002c; Frederick et al., 2003). Urban runoff is not uniform throughout all urban sites. For example, it may contain great amounts of pollution near construction sites but very low amounts in well managed areas. However, urban runoff is responsible for 16% of phosphorus, 11% of nitrogen, and 9% of sediment loads to the Chesapeake Bay (CBP, 2004). Burton and Pitt (2002) reviewed the effects of N-compounds, such as ammonia, and phosphates on aquatic wildlife. They indicated that acutely toxic doses of ammonia can increase breathing rate, cardiac output and oxygen intake, and it can lead to coma, and death. Lower concentrations can result in morphologic and pathologic changes, such as reduction in hatching success and growth rate, and changes in tissues of gills, livers, and kidneys. Nitrite and nitrate pollution can increase the mortality rate of such aquatic life as yearling rainbow trout. Phosphorus, an essential plant nutrient, stimulates the growth of algae and other aquatic plants, which can impart an undesirable smell and taste to the water and alter normal water chemistry (Burton and Pitt, 2002). Other factors affecting aquatic life are increased turbidity caused by suspended sediments, decreased light penetration and therefore prey capture for sight-feeding predators, and clogging of gills (Dennison, 1996a).

In many rural and forested environments, rainwater and snowmelt are retained in forests, wetlands and grasslands, and they therefore slowly infiltrate into the ground. Non-porous urban structures such as buildings, roads, driveways, and parking lots prevent percolation of water (EPA, 2004c; Exum, 2005). As mentioned above, the result is that water accumulates above ground and runs off in large amounts, picking up pollutants until it reaches storm drainage systems. Inside the sewers it accelerates and after released into streams, erodes stream banks, damages stream-side vegetation, and widens stream channels when released. In older cities this polluted runoff is often released without any kind of filtration (EPA, 2004a).

The volume of urban runoff, a type of nonpoint source pollution, is highly dependent on the area of impervious pavement present. The area of impervious surfaces increases along with growing land-development (Exum, 2005). World population rises every year by 1.14% (CIA, 2005) and urban areas increase accordingly (NRCS, 2000a). According to the National Resource Conservation Service (NRCS), the annual rate of land developed in the US between 1982 and 1992 was 1.4 million acres, and land development was 2.2 million acres between 1992 and 1997 (NRCS, 2000a). Land developed during this most recent period in the southeastern United States was mostly forest. For example, of the land converted to urban development, forested land accounted for 71%, 61% and 64% of that total in Georgia, Alabama and South Carolina, respectively. In the Southwest, the major part of the developed land was rangeland. For example, 66% of the land developed in New Mexico, 68% in Arizona, and 46% in California was rangeland. In the Midwest most development was mostly crop land. For example, 69% of land developed in Illinois, 67% in Iowa, and 68% in Nebraska was rangeland (NRCS, 2000b). This land conversion increases urban runoff and its associated problems.

The annual precipitation in the United States ranges from less than 13 cm (5 in) to more than 450 cm (180 in). The southeastern states, Alabama, Mississippi and parts of Florida, Georgia, Tennessee, and Louisiana, typically receive between 127 and 178 cm (50 and 70 in) annually. Rainfall amounts decrease towards the northern states and towards the western states. The Midwestern states have precipitation values of 38 and 127 cm (15 to 50 in) (decreasing towards the west). Many western states such as California, Colorado, Utah, and Wyoming show scattered areas of drought and heavy rain, including deserts and temperate rainforests where the precipitation ranges from less than 13 and 305 cm (5 to 120 in) or more.

Thus, the majority of the precipitation reaches the part of the country with more impervious surface.

Regulations

The field of urban stormwater management has evolved from being primarily the responsibility of the public works engineer to an interdisciplinary and complex field in which professionals from many disciplines work with landowners to implement best management practices (BMP) for the detention and distribution of stormwater. Overall objectives have shifted from flood prevention to water quality, infiltration, low flow protection, natural drainage, and stream restoration. Alternative solutions, such as the construction of wetlands and other bioretention which imitate nature's processes of water treatment, retention, and infiltration have become more popular. These innovative methods are intended to have less impact on the environment and to reduce future damage to the remaining natural water bodies (Randolph, 2004c). According to Randolph (2004a), the design methods in use before the 1970s were based on the "Rational Method and other rudimentary techniques." The rational method, which is often still used, uses a dimensionless rainfall coefficient along with the rainfall intensity and drainage area to calculate the maximum rate of runoff. The objectives of these methods are to provide adequate stormwater drainage from developed land and to control flood flows by upstream detention or floodwalls. In the 1970s and 1980s, the objectives were expanded to include management of new floodplain development, mitigation of storm flows closer to the source, erosion and sediment control. Best Management Practices for runoff pollution were also developed. In these decades, the design methods were based on the analysis of land use change effects on stormwater quality and quantity and size capacity modeling (Randolph, 2004c).

In the 1990s and 2000s, the design methods emphasized computer models as well as simpler sizing and design methods to determine the impacts of land use and to apply appropriate on-site measures. The management objectives gradually changed to the following (Randolph, 2004b):

- Provide adequate drainage by on-site mitigation of stormwater flows
- Provide passage of flood flows through floodplain zoning and building relocation

- Enhance infiltration to support base- and low-flows
- Treat runoff
- Maintain non-erosive channel velocities
- Protect and restore natural drainage channels

To support these goals, different laws and regulations were created. The Clean Water Act (CWA), specifically its National Pollutant Discharge Elimination System (NPDES) from the 1987 amendment, was intended to regulate stormwater discharges. The CWA requires NPDES permits for point source discharges. These permits are either issued by the EPA-approved state, or, if the state does not have a NPDES permit authority, by the EPA Regional offices. Due to limited resources, the control of point source discharges mainly focuses on publicly owned treatment works and industrial process wastewater. The NPDES permit program addresses stormwater discharges under the CWA section 402(p) (Dennison, 1996b). This section included two phases to address stormwater discharges. The Phase I program, developed in 1990, addressed sources of stormwater runoff that had the greatest potential to have a negative impact on water quality. The EPA required NPDES permit coverage for municipal separate storm sewer systems (MS4s) serving medium and large sized populations (100,000 and 250,000 people, respectively) and for stormwater discharges related to industrial activity (Dennison, 1996b). There are eleven categories of industrial activity which include construction activity that disturbs five or more acres of land. Among these eleven categories are manufacturing; mineral, metal, oil, and gas; landfill; and treatment works (Dennison, 1996b; EPA, 2004b). Case-by-case permits are issued if a stormwater discharge contributes to the violation of a water quality standard or is significant contributor of pollutants to water bodies within the United States (Dennison, 1996b).

The Phase II Final Rule included stormwater discharges that affect water quality and are not covered by Phase I (Dennison, 1996b). This rule was published in the Federal Register on December 8, 1999. This program requires NPDES permit coverage for stormwater discharges from “certain regulated small municipal separate storm sewer systems (MS4s)” and “construction activity disturbing between 1 and 5 acres of land (i.e., small construction activities).” In addition to the expansion of the NPDES Stormwater Program, the Phase II Final Rule revises the “no exposure exclusion” and the temporary exemption for certain industrial facilities from the eleven categories mentioned in Phase I. These facilities have the option to certify to a condition of “no exposure” if their “industrial materials and operations are not exposed to storm water”. As long as the condition of "no exposure" exists at a certified facility, the operator is excluded from NPDES industrial stormwater permit requirements, provided the operator notifies the permitting authority at least every five years (EPA, 2004b). The Phase II Rule also established a waiver from the application for the required permit for small construction activities. To be eligible, one of the following three conditions must apply and be certified: 1) the small construction site has a small “predicted rainfall potential,” 2) the pollutants of concern for construction activities are low at the site (based on an EPA established or approved Total Maximum Daily Load [TMDL]), or 3) “the operator can develop an equivalent analysis that determines allocations for his small construction site for the pollutant(s) of concern or determines that such allocations are not needed to protect water quality”(only for non-impaired water) (EPA, 2004b). As a result of the implementation of Phase II regulations, stormwater abatement must be addressed at many levels and even when relatively small land areas are disturbed. Summarized, both, Phase I and II, were established to reduce the discharge of pollutants to the “maximum extent practicable” (MEP), to protect water quality, and to satisfy the appropriate water quality requirements of the Clean Water Act.

Stormwater Management Systems

Several types of stormwater management facilities (SWMF) are currently used to treat stormwater in urban settings. Some of them are best used for large amounts of water; others may handle less water but have a higher efficiency of pollutant removal. When planning stormwater management for a certain area, various factors, such as size, costs, need for pollutant removal, aesthetics, hazards, and maintenance are usually considered. The following sections introduce several SWMF and describe their suitability in urban settings. Some systems described, such as Filterra® and Vortechnics®, are proprietary technologies. These have not been independently tested to our knowledge and the description provided here is based on information from the manufacturer and does not constitute an endorsement of these products.

Infiltration Practices

There are several SWMF that collect stormwater and allow it to infiltrate into the soil. These include infiltration basins and trenches, dry extended detention ponds, wet ponds, and constructed wetlands.

Infiltration trenches are rock-filled trenches that receive stormwater, whereas **infiltration basins** are shallow “ponds”. Depending on the design, stormwater might be directed through pretreatments before it reaches the SWMF. These pretreatments are designed so that large particles settle out (SMRC, 2004). **Dry extended detention ponds**, also called dry ponds, extended dry basins, detention ponds, and extended detention ponds, are designed to take up water and to detain it for a minimum duration, e.g., 24 hrs, to allow sediment particles and associated pollutants to settle out and reduce peak flows. Dry extended detention ponds do not have a permanent pool, unlike wet ponds (SMRC, 2004). **Wet extended detention ponds**, also called stormwater ponds, wet ponds, and retention ponds, are basins with a permanent water pool, either throughout the year or wet season. Incoming stormwater is treated by settling, algal uptake, and biological activity (SMRC, 2004). **Constructed wetlands** are engineered areas in the landscape that are wet most of the year. Natural wetlands, depending on their location, are also called swamps, marshes, bogs, fens, or sloughs. Wetlands are efficient in removing pollutants through microbial breakdown, plant uptake, retention, settling, and adsorption to soil (Metropolitan Council, 2003). There are two different constructed wetland treatments that can be used; surface-flow (SF) and subsurface-flow (SSF). In surface-flow constructed wetlands, water flows above the ground surface through the vegetation. In subsurface-flow treatments, water flows below surface, through permeable media containing wetland plants (Kadlec and Knight, 1996). Besides SWMFs that let water infiltrate into the ground and thus improve groundwater recharge, there are practices that filter the stormwater but discharge the water into a storm drainage system.

Practices that Direct Runoff into Storm Drainage Systems and Waterways

Many SWMF filter, detain, or treat water before it is moved off-site via a storm drainage system. These systems allow varying degrees of on-site infiltration and reduce peak flows by delaying entry of water into the storm drainage system and connected waterways.

Bioretention areas are landscaping features that treat stormwater. Stormwater reaches the bioretention area and is filtered through a system of mulch, prepared soil mix (usually highly organic), and plant roots. Water is partly absorbed by the soil mix and taken up by plants before being directed to a stormwater system by an under-drain system. An overflow structure is typically included in the design to manage large storms. Some **bioretention** systems have been designed specifically **for ultra-urban areas**. These include the Filterra® Stormwater Bioretention Filtration Systems (Americast, Ashland, VA, USA (Americast, 2004)) and several systems developed by Vortechnics® (Scarborough, ME, USA (Vortechnics Inc., 2005)). Filterra® Stormwater Biorentention Filtration Systems were designed for high volume/flow treatment with high pollutant removal. They contain a concrete container with filter media and recommended vegetation. The stormwater is directed into the container, where it is filtered before it reaches an overflow and eventually the storm drainage system (Americast, 2004). VortSentry™ and VortCapture™ are systems whose main structure is a vertical treatment chamber. Water flows into the system and is directed vertically through the treatment chamber where it is separated from floating and sinking pollutants. VortFilter™, also by Vortechnics, consists mainly of a sedimentation basin, an overflow/maintenance pipe, and VortFilter™ cartridges. Water flows into the system, and as water level rises, water is forced through the cartridges. The cartridge, according to the manufacturer, contain "customized filter media to target site-specific pollutants" (Vortechnics Inc., 2005). Different SWMF are suitable for different sites. Several factors influence the design; one of them is sizing of the system.

Size of drained area for SWMFs

In general, infiltration trench are capable of handling moderate drainage areas, whereas infiltration basins, extended detention ponds, wet ponds, and constructed wetlands are able to handle moderate-to-large drainage areas (Schueler et al., 1992). Space can be scarce in urban settings and it is therefore an important factor when deciding how to manage stormwater. Both infiltration techniques, basin/trench, and wet and dry extended detention ponds) use 2-3% of the area which drains to the system. Bioretention/Rain Gardens require 5% (SMRC, 2004). The lowest required space, 0.33% of the drainage area, is specified by the commercial systems developed by Filterra® and Vortechnics® (Americast, 2004; Vortechnics Inc., 2005). In addition to the required space for the system, peak discharge is an important design criterion.

Peak discharges of SWMFs

The primary design criterion for stormwater management systems is peak discharge. The actual peak flow allowable is determined by local regulations and local watershed characteristics. The control of more than one design storm is often required by local regulations. Retention of a 2-yr. peak discharge is a common requirement. A return period of 2 years indicates a storm event that would be expected to occur, on average, every two years. For natural watersheds, a 2-yr storm typically fills streams to the top of their banks (Schueler, 1987). Some jurisdictions require also a 10-yr. or even a 100-yr. storm design. Infiltration BMPs generally are designed to handle smaller storm events than ponds BMPs (Schueler, 1987). Wet and dry extended detention ponds are commonly designed to control 2-, 10-, and 100-yr. storms, whereas infiltration basins and trenches, depending on their design, may not be able to control a 100-yr. storm (Schueler, 1987). In addition to peak flow, the pollutant removal of the system is an important factor to consider.

Pollutant removal

The pollutant removal efficiency of SWMF is an important factor, considering the conditions of water bodies and their effect on wildlife and human health. The following table shows pollutant removal data found in the literature for each SWMF described above:

Table 1.2) Pollutant removal data (in %) for various stormwater management systems summarized from (Metropolitan Council, 2003; SMRC, 2004; Winter, 2000)

Stormwater Management Facility Type	TSS*	TP**	TN***	NO_x	Metals	Bacteria
Infiltration Basin	75	60-70	55-60	N.A.	85-90	90
Infiltration Trench	95	70	51	40	26 for Cu and Zn	N.A.
Dry Extended Detention Pond	47	19	25	43	Cu 57 Zn 66	78
Wet Extended Detention Pond	80	51	33	43	Cu 57 Zn 66	70
Constructed Wetlands	67-80	48	69-76		Cu 67 Zn 44	N.A.
Bioretention	81	29	49	38	51-71	58
Filterra®	88	74	68		82 (e.g. Cu)	N.A.

*TSS: total suspended solids
**TP: total phosphorus
***TN: total nitrogen

Pollutant removal clearly varies between different systems. For non-ultra urban areas, infiltration trenches have high phosphorus and suspended solid removal rates. Constructed wetlands have comparably high nitrogen removal rates and extended detention ponds are described as being effective at NO_x removal. A system that includes both infiltration trench features and plant material may increase the pollutant removal capacity of the SWMF.

Costs associated with SWMFs

Municipalities, like most agencies, are monetarily limited. It is important to find the most suitable SWMF for a given situation that optimizes stormwater treatment economically. Maintenance costs of various SWMF can vary immensely and need careful consideration (SMRC, 2004). Since these costs depend on factors such as location, it is difficult to present comparable data. In general, extended detention dry ponds are the most cost effective BMP in their size range. Wet ponds have moderate-to-high costs compared to extended detention dry ponds; constructed wetlands are marginally higher in price than wet ponds. Another cost effective method for small sites are infiltration trenches, but the rehabilitation costs may be high. High rehabilitation costs seem to be valid for infiltration basins as well, in addition to high construction costs (Schueler et al., 1992).

Overall, costs vary greatly between different stormwater management techniques. Some, such as infiltration trenches, are only cost effective on small sites whereas others, such as extended detention dry ponds, are most cost effective where there are no space restrictions. This needs to be considered when designing a SWMF for a certain site to avoid undersizing while still providing sufficient management for a given site and budget.

Maintenance activities and longevity of SWMFs

In general, wet ponds and infiltration trench are considered to require low maintenance, whereas dry extended detention ponds and infiltration basins have high maintenance requirements (EPA, 1993; Schueler et al., 1992). Most systems require annual or semi-annual inspections, such as wet extended detention ponds, infiltration basins and trenches, bioretention, and dry extended detention ponds. These inspections are mainly conducted to detect damage or for bioretention, removal and replacement of dead or diseased vegetation. All four practices, except bioretention, require a 5- or 5-7-yr. maintenance and both detention pond practices even 20- or 25-50-yr. maintenance. Maintenance should include activities such as removal of sediments or groundcover restoration (SMRC, 2004). Maintenance activities and costs vary to a great extent. Besides construction and maintenance, the longevity of the system also influences total costs. Costs might be very high for a system that needs to be replaced regularly compared to a system with high longevity. Infiltration basins have low longevity, whereas constructed wetlands and dry and wet extended detention ponds provide stormwater treatment for a long period of time. Knowing the features provided and required by the system is essential when designing a SWMF.

Secondary effects of SWMFs

The aesthetics and potential hazards created by SWMF have generally not been quantified. Facilities with a permanent water table, such as wet extended detention ponds and wetlands, can be a suitable environment for mosquito populations and thus a health hazard to humans. In addition, some SWMF, such as dry extended detention ponds, are unaesthetic and may lower the value of adjacent properties by 3-10% (SMRC, 2004). Others, such as wet extended detention ponds, can be aesthetically valuable due to their design and vegetation, and can increase the value of nearby homes by 15-25% (SMRC, 2004). The systems by Filterra® are described to "add beauty and value to the landscape" because of the included plantings (Americast, 2004). Likewise, rain gardens and other bioretention systems can be landscaped in a variety of ways that can add aesthetic value to a site.

Summary

Stormwater management systems can be space-consuming, which can be challenging in urban areas where available space can be very limited. Some practices may decrease the value of adjacent properties because they detract from site aesthetics (e.g., dry extended detention ponds). Finding a suitable site and constructing stormwater management systems can be a challenge when the systems are added as retrofit for a previously developed site.

Costs, sizing, pollutant removal, aesthetics and other factors need to be considered when designing a SWMF. Pollutant removal is a very important factor to protect the environmental conditions of water bodies and thus wildlife and human health. Some SWMF increase or decrease the value of adjacent homes due to their aesthetic value. Direct and indirect costs need to be considered since budgets are always limited. A critical limitation for a municipality is space, especially in urban areas. In 2002, Quigley, described in a 'Local Community Resources' fact sheet the possibility of using structural soil, a gravel-soil mix, to improve water quality (Quigley and Lawrence, 2002). He proposed incorporating the absorption of parking lot runoff into landscape islands, also called bioretention islands, that would benefit stormwater management without necessarily providing the quality control or the capacity for retention of large storm events (Quigley and Lawrence, 2002).

Combining construction elements such as parking lots or streets with a stormwater management facility would save space and would not detract from landscape aesthetics. It could also potentially provide large water uptake capacity and reduce urban runoff. Incorporating vegetation, especially large trees, would increase the canopy cover and thus rainfall interception, and these trees would to take up water which than would not have to be managed by a SWMF. Trees in urban areas have various other benefits, such as pollutant removal from the air, wind protection, and shading. However, growing trees in the urban environment can be challenging because space conditions, below and above ground, are often not suitable for trees to grow to their full size. Large trees mitigate stormwater more effectively than small trees (Xiao and McPherson, 2003); therefore, an ideal stormwater management facility would provide conditions to allow trees to achieve a large size.

Environmental Conditions in Urban settings

Pavement generally requires a heavily compacted subgrade to assure a high load-bearing capacity and long-term pavement stability. For this reason, topsoil is generally removed and the subgrade is compacted. Depending upon climate and soil conditions, crushed stone is then spread and compacted. This base layer of granular material is required to have a low water holding capacity since water just below pavement could cause pavement failure, especially in cooler climates where winter freezing is common. One result may be little water and nutrient availability for the tree in that area. If the subsoil is compacted properly, the resulting high soil strength will severely reduce root penetration and influence root growth direction (Kozlowski, 1943; Materechera et al., 1991). The soil strength achieved, however, also depends on the soil particle sizes distribution. The smaller the particle size, the greater the penetration resistance at a lower bulk density compared to soils with large particle sizes (Daddow and Warrington, 1983; Day et al., 2000). When these soils dry, the soil strength becomes even higher (Clark et al., 2003), which also decreases the infiltration rate (Bassuk et al., 1998; Day and Bassuk, 1994). In addition, the compacted subsoil often occurs within inches of the pavement because of the high excavation costs of large areas

(Kalter, no date-a). Consequently, the tree has a very small available soil volume and is surrounded by either impenetrable material or material that has little water or nutrients. Root restriction limits plant growth (Kozlowski, 1943; Nesmith et al., 1992). Lindsay and Bassuk developed a general rule that estimates soil volume suitable for a tree as 0.06 m^3 (2ft^3) soil per 0.03 m^2 (1ft^2) crown projection (Lindsey and Bassuk, 1991). Lipiec and Hakansson (2000) evaluated plant responses to soil compaction and high water tension. They found that the greater the relative compaction, "the higher was the water tension (the lower the water content) at which aeration became critical, and the lower was the water tension (the higher the water content) at which penetration resistance became critical." Krizek explains that like bonsai trees, trees in urban settings are rooting-volume restricted, but unlike bonsai trees, they are not pruned accordingly to maintain a balance between absorption and transpiration. He indicates that this balance determines the development of internal water stress, so that species with high top:root ratios have low survival rates (Krizek and Dubik, 1987).

Roots of some tree species (e.g., *Acer saccharinum*) are able to grow into moderately compacted soil when soil wetness reduces root penetration resistance, but other species (e.g., *Cornus florida*) are not (Day et al., 2000). Roots generally tend to take the path of lowest resistance, which in urban conditions can be cracks and the interface between pavement and the base layer. Once growing in these spaces radial growth often leads to pavement lifting (Grabosky et al., 2004). Pavement lifting results in costs of about $100 million per year in the U.S. (Smiley, 2005). In addition to the costs of pavement damage, the repair of pavement often causes tree decline or death (Grabosky et al., 2004). Trees in urban settings usually die prematurely (Foster and Blaine, 1978). One key reason for premature tree mortality in urban settings is water stress (Evans et al., 1990). This water stress is thought to often be a result of lack of water reaching roots due to collection by catchment areas or restricted infiltration by impervious surfaces (Grabosky and Gilman, 2004). The same work by Grabosky and Gilman (2004) described tree growth for different areas of open surface in a parking lot design. They found that tree growth decreased with decreasing area of nonpaved surface for four out of five tree species. Growth of *Ulmus parvifolia*, *Platanus occidentalis*, *Quercus shumardii*, and *Quercus laurifolia* declined as the impervious surface area increased, whereas growth of *Quercus virginiana* did not. This growth reduction can be due to the elevated soil temperatures, water limitations, and high soil strength due to compaction (Grabosky and

Gilman, 2004). In addition to water stress and reduced aeration in the root zone, other stresses are heat stress above and below the pavement, high salt levels, modified pH (usually alkaline) (Evans et al., 1990), nutrient deficiency and toxicity, and accumulation of soil gases (Krizek and Dubik, 1987). Graves (1998) described how elevated soil temperatures affect physiology and growth of root and shoot systems of trees. He says that "slight increase of the root-zone temperature above 32 ºC (89.6 ºF) can result in reduced growth and water uptake of roots, reduced surface area and stomatal conductance of leaves, stunted stems, and alterations in nutrient content." A soil temperature of 36 ºC (96.8 ºF) reduces root extension, shoots elongation, leaf area, and dry weight, plant water potential, stomatal conductance, and lowers the chlorophyll concentration in leaves. He also explained that the urban heat island extends below ground. Celestian and Martin (2004) found that surface temperature was 59.4 ºC (138.9 ºF) for asphalt, 47.5 ºC (117.5 ºF) for concrete, 44.1 ºC (111.4 ºF) for decomposing granite rock mulch, and 32.8 ºC (91 ºF) for turf, leading to higher rhizosphere temperatures (30 cm [11.8 in] depth) under asphalt and the lowest under turf. Halverson and Heisler (1981) tested the soil temperature below a parking lot tree site, an asphalt-covered site, and a "control-site". They found that the soil temperature, at a 15-cm (5.9-in) depth, at the tree site was 3 ºC (37.4 ºF) higher, and at the asphalt site 10 ºC (50 ºF) higher than the control. Montague and Kjelgren's research (2004) results agree. They investigated energy balances of different urban surfaces and found more energy was conducted into soil below asphalt and concrete (and thus the soil temperature was higher) compared to pine bark and lava rock mulch.

In summary, trees are exposed to numerous unfavorable conditions when planted in urban settings. They have to cope with too little water or air, nutrient deficiencies or toxicities, alkaline and saline soil, low rooting volume, and high soil temperatures. The consequence of these conditions is often premature tree death. Giving trees a greater penetrable soil volume could increase tree health and thus general resistance to biotic and abiotic factors.

Structural Soil

Structural soils consist of a stone and a soil component, forming a matrix with a high load-bearing capacity (Fig 1.1 [Specifications Appendix I]). CU® Structural soil is a gravel soil-mix developed at Cornell University, Ithaca, NY, in the mid 1990s to address one of the central issues limiting tree growth in urban areas: restricted soil volumes that limit root development (patented in 1998 under U.S. Patent # 5,849,069: Urban tree soil to safely increase rooting volume (USPTO, 1998)). The primary objectives of the structural soil research were to create a substrate that would both allow for adequate tree root growth, and support pavement for sidewalks, streets, and parking lots (Grabosky and Bassuk, 1995). As previously described, trees are commonly surrounded by severely compacted soils to meet engineering standards. These soils are very inhospitable to tree roots. In addition, root growth is restricted, leading to low stability and decreased capability of the tree to take up water and nutrients. Grabosky and Bassuk wanted to develop a soil with a high load-bearing capacity that would also contain large voids. A high load-bearing capacity is needed to fulfill the necessary requirements to assure success of the pavement structure (Grabosky and Bassuk, 1995). The large voids could partially be filled with soil, water, and air (Grabosky et al., 1999), but also allow root penetration so that even when the soil is highly compacted, trees have improved rooting conditions (Grabosky et al., 2002). The soil component cannot have such a volume that it over-fills the voids, but it has to be adequate to meet tree requirements (Bassuk et al., 2005).

Other structural soil mixes have been developed, such as a mix containing Carolina Stalite as the stone component (Costello and Jones, 2003). Carolina Stalite is a heat expanded slate, which is lightweight and offers high soil strength (Carolina Stalite Company, Salisbury, NC).

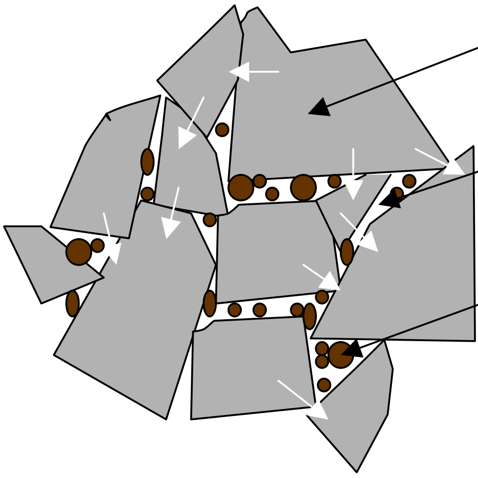

Figure 1.1) Scheme of structural soil matrix (adapted with permission from Grabosky et al., 1999).

Several studies have evaluated structural soil behavior in urban settings. Grabosky and Bassuk (1995) compared root development of *Tilia cordata* trees in clay loam with root development in structural soil and found that roots in the stone-soil mixes grew at least 320% wider and deeper than roots in conventional soil. In 1996, the same group published their study of *Quercus rubra* seedlings grown in compacted stone-soil mixes and clay loam (control) compacted to meet engineering standards. Root growth of seedlings in the stone-soil mixes was greater than those grown in the compacted clay loam (Grabosky and Bassuk, 1996). In 1998, Grabosky et al. supported the performance of compacted structural soils, by observing greater and deeper root growth and better tree health in this medium compared to a standard sidewalk treatment. Bassuk et al. (1998) published specific recommendations for the use of structural soil in the same year. They recommend using gap-graded gravel, made up of crushed stone (1.3-3.8 cm; 0.5-1.5 in), clay loam, and hydrogel in ratios of 100:20:0.03, by weight, with total moisture of 10% at mixing. They recommended the water content of the mix be standardized, because water acts as a lubricant; therefore, higher water content results in a higher bulk density with equal compaction effort.

Porosity of structural soils

Grabosky (1999) describes percent air voids and percent voids in mineral aggregate (skeleton voids) for structural soils with different amounts of clay-loam. Depending on the soil content, about 27% of the soil mix can be filled with air, water, or roots. With 12.4% soil, there are 29.4% air voids, where there are only 26.4% air voids when using 19.8% soil. He describes in another work results for porosity between 24% for a stone to soil ratio of about 4:1, and 29% for a stone to soil ratio of about 7:1 (Grabosky and Bassuk, 1995).

In summary, the amount of voids is directly related to the amount of soil in the system. It is important to have a suitable amount of soil within the mix to support tree growth, while still allowing sufficient aeration and nutrient availability.

Compaction of structural soils

Proctor density is a standard method to describe compaction. It determines the relationship between water content and dry weight of soils (ASTM, 2003). With increasing moisture content, bulk density increases by equal compactive effort with increasing moisture content, because the water functions as a lubricant, up to an optimum. Above this optimum, water, being incompressible, prevents the soil from compaction, which leads to a lower bulk density. Therefore, the maximum occurs at the optimum water content.

Soil strength

Soil strength is the capacity of a soil to withstand forces without collapsing. The California Bearing Ratio (CBR) is one way to describing the strength of materials used under pavement (ASTM, 2003). A CBR value of 100 describes equal properties of the tested material and the reference material. Subgrade often has a relatively low CBR of 5-10, whereas the base material would have 40-80. These data would be adequate for low traffic pavement, such as sidewalks (Grabosky and Bassuk, 1995).

Structural soil is described to have a Proctor density of 95% and should have a CBR of over 40 (Grabosky and Bassuk, 1996; Kalter, no date-b), and it therefore has a load bearing capacity sufficient to fulfill engineering requirements as a medium below streets and sidewalks.

Benefits of Trees for Urban Sites

There are various potential benefits of trees to air and water quality and human wellbeing. Konijnendijk et al. (2005) dedicate an entire chapter of the book, 'Urban Forests and Trees' to benefits and uses of urban forests and trees. Trees give us a great environment for recreation and improve the home and work environment and mental health. This is partly because of the various colors, sized, shapes, and textures we can choose from when designing a landscape. In addition to the aesthetic benefits, trees are a useful tool for wind and climate control, air pollution reduction, flood and erosion control, and sound control. In economic terms, trees can increase property values (Harris et al., 2004; Konijnendijk et al., 2005; Tyrvainen, 1999) by an average of 7% (Harris et al., 2004). Surveys determining the effect of trees on patronage showed that the time and money spent in a business district can be increased when trees or mixed vegetation are planted and even the time patrons are willing to take to reach these areas is longer than for business districts without tree planting or mixed vegetation (Wolf, 2003). It is also reported that the greener the areas surrounding buildings are, the fewer crimes occur (Kuo and Sullivan, 2001).

Trees are capable of removing pollutants from both air and soil and can reduce the amount of atmospheric carbon (Nowak, 1993). Trees are also effective in removing O_3 and PM10 (air borne particulate matter with a particle size of less than 10 microns) from the air (Salwasser and McPherson). Poplar plantations are very effective at removing pollutants from the soil and have an average removal rate for nutrients like nitrogen, phosphorus, and ammonium of above 75% (Szabo et al., 2001).

Trees also remove water through transpiration, which could contribute to a stormwater management system. Trees have a water use efficiency of 200-400 kg H_2O/kg dry mass produced (Marshall, no date). This results in transpiration rates of about 40,000 L (10,566 gal) per summer for a large deciduous tree or about 300 L (80 gal) per day (Thomas, 2000). Cermák et al. state 65-140 L (17-37 gal) per summer day for mature maple trees (Cermák et al., 2000). Factors, such as species, size, leaf area, and location influence the water use of trees.

Big, healthy trees could be a great contributor to a stormwater management system because they transpire a lot of water that would not have to be stored in a SWMF. In addition, they can offer air- and soil-pollutant removal, aesthetic value, economic and ecological benefits.

Objectives

We are testing the use of structural soil and trees as a stormwater management system in urban settings. The proposed system uses a minimum of 61-cm (24-inch) deep structural soil beneath a base layer that is either covered with pervious or impervious pavement. Using the latter, additional consideration must be given to conveying water below the pavement.

Such a system could provide a number of benefits, but it also raises a number of questions that must be addressed through research. Benefits would be stormwater management on site, which could reduce runoff and increase groundwater recharge through infiltration. Benefits of trees in such a system include rainfall interception, pollutant and water removal, and aesthetic value. General questions include: How do trees thrive in such system? What are potential contributions of trees to it? How would the water quality be affected?

To meet these objectives, the following tasks were conducted:

1) Determine how trees thrive in fluctuating water tables which might be expected in a stormwater management system utilizing structural soil

2) Estimate how much water they take up in such fluctuating water tables

3) Evaluate whether or not tree roots grow into compacted subsoil and evaluate the effect of tree roots on the infiltration of stormwater into clay subsoil

Chapter 2: Can Tree Roots Penetrate Compacted Subsoils and Improve Infiltration for Stormwater Management?

Introduction

Urbanization results in increasing areas of impervious surface which consequently leads to more urban runoff. The Natural Resources Conservation Service (NRCS) describes an increase in developed land from 72.9 million acres in 1982 to 108.1 million acres in 2003 (NRCS, 2003). This is an increase of about 34% and is a rate of about 1.7 million acres every year. The overall quantity of runoff from a developed area can be more than four times as high as runoff from a wooded area after a 2-yr. storm event. The peak discharge for the same storm event can be almost 12 times as high for the developed area compared to the wooded one (Horner, 1994). The quality of water bodies is adversely affected by urban runoff because of the great amount of pollutants, such as sediment, oxygen-demanding substances (organic matter), nutrients (phosphorus, nitrogen), toxic substances, bacteria (Dennison, 1996b), viruses, and heavy metals (EPA, 2004a) carried by the runoff. This pollution jeopardizes environmental conditions required for wildlife and human health (EPA, 2004c). Urbanization and the consequent pollution of water bodies are expected to continue. The Clean Water Act, a United States federal law established in 1972, was created to decrease pollutant discharges, control non-point source pollution and sustain water quality for wildlife and recreation (EPA, 2002a) There is great room for improvement to current on-site stormwater management facilities to reach these goals.

Trees can be a very useful tool for handling stormwater. They intercept rainfall and thereby decrease the amount of water reaching the ground by temporarily storing rain water on the canopy surface (Xiao and McPherson, 2003). They also direct precipitation into the ground through trunk flow, and they take up pollutants (Szabo et al., 2001) and stormwater (Cermák et al., 2000; Marshall, no date) through their roots. Trees are also a much appreciated feature in urban areas since they improve life quality in many ways.

One policy of the Clean Water Act is to make a major research and demonstration effort to develop the technology necessary to eliminate the discharge of pollutants into navigable water (EPA, 2002a). One proposed method for controlling stormwater on site is to use a structural soil reservoir, e.g., a parking lot with trees in which stormwater can infiltrate and slowly seep into the ground.

Structural soils are media with a stone and a soil component. The stone component, making up about 80% by weight, provides a matrix which even after compaction contains large voids (Costello and Jones, 2003). This combination offers a high load bearing capacity and still has the porosity to be penetrable by roots or filled with air or water. Soil partially fills these voids and offers nutrient and water holding capacity to support tree growth (Bassuk et al., 2005). Since structural soil surrounds the trees in such systems and is easily penetrable, trees will likely become larger and healthier and offer higher rainfall interception, transpiration rates, and more pollutant removal. The more water the tree takes up and the higher the infiltration rate of the subsoil, the greater is the overall stormwater capacity of the structural soil reservoir to take up water.

Trees are an integral part of this system in that they will intercept rainfall and their roots will remove water from the stormwater retention area. We would like to determine if penetration of the subsoil by tree roots improves the native infiltration rate of a given subsoil. Although high soil strength can inhibit root penetration (Barley, 1963), bottomland species may be better adapted to penetrating high density soils when the water content is high (Day et al., 2000). Therefore, we chose two bottomland species to determine:

1) Will tree roots grow into compacted subsoil?
2) Will tree roots increase the infiltration rate of compacted soil through the developed root channels?

Knowing the contribution of trees to a stormwater management facility (SWMF) will help determine the importance placed on their inclusion in urban designing and the resources appropriated to their maintenance.

Material and Methods

Experimental Design

The experiment was conducted at the horticultural greenhouses on the Virginia Tech campus in Blacksburg, Virginia, USA. Red maple (*Acer rubrum* L.) and black oak (*Quercus velutina* Lam.) trees from Heritage Seedling Inc., Salem OR, were used in addition to a no-tree control. In February 2006, 2-yr.-old bare-root seedlings of both species were planted in a cylindrical reservoir of pine bark (2.18 L; 0.58 gal) in the center of 26.5L (7 gal) containers, with subsoil on all sides and below the pine bark (Fig. 1). This subsoil was a clay (15.4% sand, 35.3% silt, and 49.4% clay) from the B horizon of a Groseclose soil (Fine, mixed, semiactive, mesic Typic Hapludults) from Montgomery County, Virginia and was compacted to two different degrees, severe and moderate. No-tree controls were constructed in the same way for each compaction level.

Thirty containers were placed in a completely randomized design with five replications of 3 treatments (two species + no-tree) x 2 compaction levels (severe and moderate).

Figure 2.1) Left: scheme of infiltration experiment setup. Right: picture of the set up of the containers in the child pools.

Severe Compaction

26.5 L (7 gal) containers were evenly filled to 16-cm (6.3-in) height with clay loam. A tightly fitting wooden board was laid on top and struck 20 times from 50.8 cm (20 in) above the board with a 4.54-kg (10-lb) proctor hammer. The board was removed and a 15.2-cm (6-in) diameter PVC pipe was placed in the center and surrounded by clay loam to the 32-cm (12.6-in) mark. A wooden ring was then placed over this soil ring and struck 20 times from 50.8 cm (20 in) by the proctor hammer. The PVC pipe was removed and a 15.2-cm (6-in) diameter PVC ring, 10 cm (4 in) in height, was placed 5 cm (2 in) below the soil line to serve as a collar for the infiltration measurements, before filling the center with pine bark and planting the tree (no tree for the control).

Moderate Compaction

The containers (26.5 L; 7 gal) were evenly filled to 14-cm (5.5-in) height with clay loam. A tightly fitting wooden board was fashioned from 2-cm (0.75-in) thick pine plywood and placed on top of the soil. The board was struck ten times from a 50.8-cm (20-in) height by a 4.54-kg (10-lb) proctor hammer. The board was removed and a PVC pipe was placed as described above and surrounded with 14 cm (5.5 in) of clay loam. Using the wooden ring, the clay loam was compacted with ten blows from 50.8 cm (20 in) with a 4.54-kg (10-lb) proctor hammer. After removing the PVC pipe, a collar was placed and the seedling planted as described for the severe compaction treatment.

Figure 2.2) Right: compaction of the bottom layer using a wooden board and a 10 lb Proctor hammer. Left: Compacted bottom soil layer

 

Figure 2.3) Right: compacted soil with cylinder in the middle which will be filled with pine bark. Right: containers with compacted soil, pine bark in the center and a tree

Soil Bulk Density

Three undisturbed samples were collected per treatment. One container without a tree was chosen and two samples from the side and one from the bottom, in the center below the rootball, were taken. The samples, 92.367 cm^3 (5.63 in^3) were taken with a slide hammer, and dried at 105ºC (221ºF) to a constant weight and the bulk density calculated. Both, the side and the bottom, for each treatment, were conducted the same way, with the same number of blows. Since the surface area was greater of the bottom layer than the side layer, it may be that the side has greater compacted soil, higher bulk density, than the bottom.

Infiltration Measurements

Containers were flooded for two days to bring the soil to saturation before measuring the infiltration rate. To ensure complete saturation, we filled portable child swimming pools (Fig. 2.1) with water for two days and allowed the water to reach the soil surface from the bottom of the container through capillary action. Infiltration rate was measured on six dates during the course of the experiment, 15 May, 15 June, 9 and 20 July, 3 August, and 6 September 2006. After complete saturation of the soil-pine bark system, 1 L (0.26 gal) of water was poured into the PVC collar and the time necessary for the water to infiltrate the system (no water being visible on the pine bark surface) was measured. This was repeated once, adding up to two subsamples. Because the system was saturated, this measurement provided a relative measurement of saturated hydraulic conductivity of the slowest part of the system (the subsoil in this case).

Root Growth

In Sept 2006, root presence vertically and horizontally was determined by cutting 2-cm (0.79-in) slices off the soil, starting from the bottom (Fig.2.2), and counting the root tips. Since the container tapers towards the bottom, surface areas were 706.9 cm^2 (109.6 in^2; bottom) and 855.3 cm^2 (132.6 in^2), respectively. The containers were cut using a jig-saw at 2 cm (0.79 in) and then the soil cut with a hacksaw. A brush was used to clean the soil surface so we were able to see and count all root tips. After that, a second 2-cm (0.79-in) slice was cut, and the root tips were counted here as well. For both bottom layers, because of the great number of root tips in most containers, the root tips were counted on two triangular samples each 1/8 of the entire area (Fig. 2.3, left) and calculated for the entire area. A 2-cm (0.79-in) slice was cut from the side and the soil was cleaned and roots were for a 130-cm^2 (20.2-in^2) area centered horizontally on the soil face to capture roots emerging from the pine bark (Fig. 2.3, right). A second slice was cut (2 cm; 0.79 in), surface cleaned, and the roots were counted for the same size area. The root counts were calculated per init (cm^2) surface area.

All experimental data were analyzed by analysis of variance with the GLM procedure of SAS (vers. 9.1, SAS Institute, Cary, NC). Root counts were transformed by taking the square roots before analysis since distribution of count data is Poisson (not normally distributed), and means and variance are not independent (Sokal and Rohlf, 1995).

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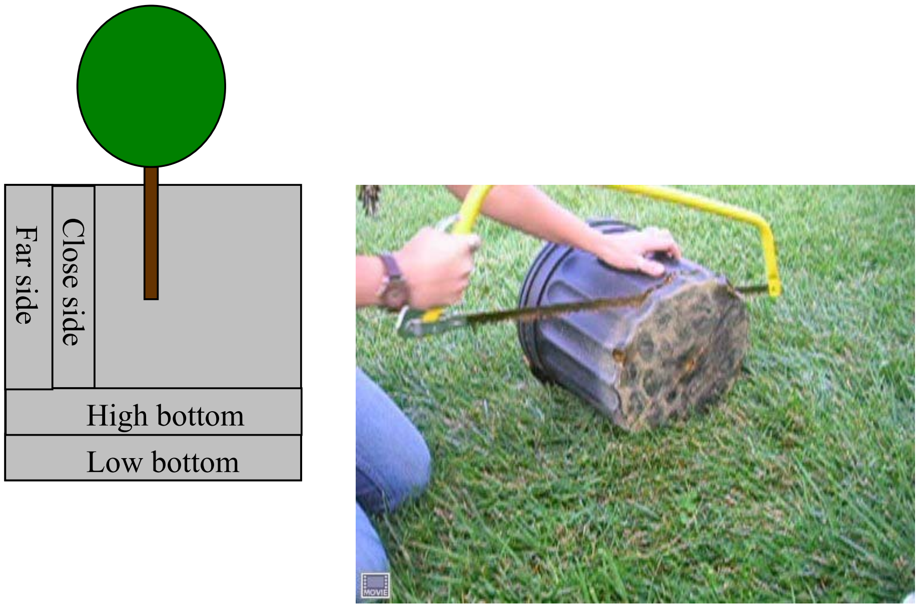

Figure 2.4) Left: scheme of the container and the location of the 2-cm slices that were cut off for root counts. Right: cutting of first 2-cm slice from the bottom of the container to then brush and count the root tips for root growth analysis.

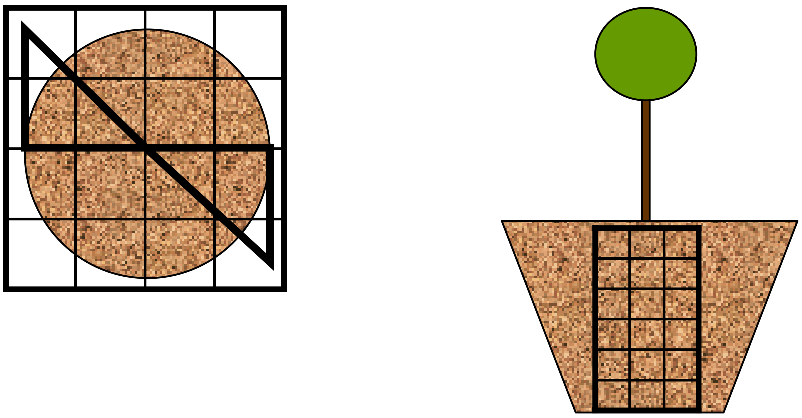

Figure 2.5) Scheme of root count location. Left: bottom layer with two triangular shaped sample areas in which the roots were counted. Right: side layer with grid in which roots were counted

Results and Discussion

Infiltration

There was strong evidence that the presence of *Quercus velutina* and *Acer rubrum* trees increased the infiltration rate through the subsoil (shorter time of infiltration) relative to containers that did not have trees (Table 2.1). This supports the hypothesis that the infiltration rate of a soil can be increased through root channels. Bramley et al. (2003) investigated whether flood water infiltrates through root channels. They selected two groups of *Eucalyptus largiflorens* trees within a floodplain, flooded them by filling 1,500 L (396.3 gal) water into impoundments constructed around the trees, and measured the time of infiltration. They also built impoundments and tested drainage on similar areas without trees. They found flood water around trees infiltrated 2 to 17 times faster when the trees were present than in soils without trees. In laboratory experiments, Whalley et al. (2004) investigated the effect of root deformation of the soil and root exudates on water movement through the soil to the root of maize plants. Their results suggested that water transport through the soil adjacent to the root was lower than through the bulk soil. In field situations with trees, where root turnover is high, this effect might be expected to be diminished as roots grow and die, leaving root channels behind. Black et al. (1998) tested the longevity of roots of different 1-yr.-old tree species with minirhizotrons and found that 60% of *Prunus avium* roots and even 94% of *Picea sitchensis* roots died within 14 days. In the present study, roots had the opportunity to grow completely through the soil profile in the containers. In practice, the effect of root channels on infiltration is influenced by the permeability of soil regions below the rooting area.

For both compaction levels and for every measurement date except one (9 Jul Moderate Compaction), soils with *Q. velutina* trees drained more rapidly than those with *A. rubrum* trees. However, variability was high and there is a high probability that this difference is due to factors other than species (see p-values in Table 2.1.). Further study may be merited on the influence of species on the effect of root penetration on drainage. In this case, the general difference in root structure of the two species could influence results. *A. rubrum* has a rather shallow but widespread and fibrous root system, whereas *Q. velutina* initially produces a deep taproot with some widespread and deep lateral roots (Hightshoe, 1988). In addition, the *A. rubrum* trees were infested with mites and thrips during the first period of the experiment which depressed growth and might have affected root development.

The time of infiltration for both species and the no-tree control was shorter for the moderately compacted soil than the severely compacted ones. This is presumably due to greater porosity of the moderately compacted soils compared to the severe compaction treatment.

Overall, combining all dates and both tree species, trees decreased the time of infiltration by about 63% (+/- 2%) compared to the no-tree containers. This was similar for both compaction treatments. It shows a great potential for trees to increase the infiltration rate and potentially the capacity of a stormwater management system utilizing structural soil. However, these results are for *Q. velutina* and *A. rubrum* seedlings in a system that forces roots to grow into the surrounding subsoil. Whether this is the case in a larger system with sufficient penetrable soil volume above the compacted subsoil needs to be investigated. Nevertheless, depending on the species, plants can penetrate strong soils.

Our results did not indicate that the infiltration rate changed over time. The first date of infiltration rate measurement was three month after planting. Although they were dormant at planting, trees were likely well established at the first measurement date. Considering a higher infiltration rate for the containers with trees, roots potentially penetrated the soil before the first measurement was taken and did not further increase the infiltration rate. In this study, measurements did not capture that time period between planting and establishment that might have been expected to show an increase of the infiltration rate over time.

In stormwater management, a geotextile would normally be used to separate the structural soil from the subsoil. Geotextile consists of woven material which might be a barrier for soil, but tree roots are frequently observed to grow through geotextiles (personal communication, SD Day, Virginia Tech, Blacksburg, VA). We would therefore not expect geotextiles to impede root growth.

Urban soils are very disturbed from excavation, soil movement to or from other locations, soil compaction, and other human modification (Craul, 1992). This results in the absence of natural soils (especially upper horizons), a greatly reduced organic component, high bulk density through compaction, and the lack of the normal nutrient cycle (Konijnendijk et al., 2005). Soils used in this container experiment were also disturbed, since they were excavated, transported, filled into the container and compacted. The bulk density of the soil in our experiment was 1.3 g/cm^3 (0.75 oz/in^3) for the moderate and 1.6 g/cm^3 (0.92 oz/in^3) for the severe compacted soil, which is within the range of expected bulk densities of urban soils. Urban soils can have bulk densities as high as 2 g/cm^3 (1.15 oz/in^3) (CWP, 2003). Both subsoils, the ones used in this container experiment and in urban settings, are disturbed and may have experienced the same types of impacts and structural changes. Therefore, the soils in our experiments may be in comparable conditions to those found in land under development, which would increase the informational value of this research.

Depending on the design of a SWMF utilizing structural soil, trees may develop a very extensive root system, which may or may not be contained exclusively in the structural soil reservoir. The degree that rooting within structural soil can be expected to affect infiltration rates below the system needs to be more thoroughly investigated. Considering the sizing of common parking lots which may provide a suitable size for such SWMF, trees in such a stormwater facility may not get the chance to build a root system large enough to affect the infiltration rate of the system unless they are specified to be planted in sufficient density. In addition, high water tables resulting from extremely slow draining systems may restrict downward root growth.

Overall, the results suggest that trees have the potential to increase the capacity of a SWMF utilizing structural soil through root growth into the subsoil that provides channels for water flow. This experiment used two species which are rather tolerant of waterlogged soils (Burns and Honkala, 1990). This tolerance may also confer some ability to penetrate compacted soils (Day et al., 2000). A long-term experiment in the field with a greater variety of species would answer more questions that this experiment was unable to address.

Table 2.1) Effect of red maple (*Acer rubrum* L.) and black oak (*Quercus velutina* Lam.) on time required for water to drain through soil profile when compacted at two levels.

Severe Compaction	15 May[z] (seconds)	15 June (seconds)	09 July (seconds)	20 July (seconds)	03 Aug (seconds)	06 Sept (seconds)
maple	133.6 (19.2)	131.6 (15.5)	211.8 (57.6)	125.0 (16.0)	149.3 (16.0)	244.2 (75.3)
no tree	158.6 (11.5)	225.2 (8.0)	475.9 (59.7)	173.3 (27.6)	253.7 (37.8)	943.3 (274.2)
oak	101.4 (12.7)	109.5 (23.5)	156.4 (52.9)	123.0 (14.2)	137.0 (28.4)	135.1 (28.4)
Moderate Compaction						
maple	51.9 (13.4)	66.7 (14.4)	139.5 (40.1)	72.3 (20.9)	150.9 (60.4)	103.0 (31.2)
no tree	94.4 (13.2)	171.9 (23.6)	495.7 (107.4)	187.1 (25.7)	267.0 (63.6)	239.0 (39.3)
oak	39.5 (5.9)	41.8 (5.0)	153.6 (74.6)	55.9 (9.5)	69.0 (17.5)	84.4 (17.4)
	$P > t^y$					
Severe Compaction						
maple vs. no tree	0.195	0.001	0.012	0.101	0.090	0.001
oak vs. no tree	0.006	0.001	0.003	0.089	0.060	0.001
maple vs. oak	0.100	0.355	0.575	0.945	0.837	0.554
Moderate Compaction						
maple vs. no tree	0.032	0.001	0.001	0.001	0.061	0.435
oak vs. no tree	0.007	0.001	0.002	0.001	0.003	0.376
maple vs. oak	0.516	0.298	0.887	0.567	0.179	0.915

[z]Trees planted on 10 Feb, 2006. Numbers are mean 5 replications (2 subsamples per replication) and are not transformed. SE mean in parentheses.

[y]Contrast *P*-values were calculated by PDIFF within the GLM procedure of SAS.

Root Distribution

Roots of both tree species grew into the surrounding subsoil. There were roots in all layers analyzed. A number of containers also showed roots growing out of the bottom during the course of the experiment. There was no evidence that compaction level influenced root distribution in either species (Table 2.2). This indicates that *Q. velutina* and *A. rubrum* seedlings are equally capable of penetrating soils of different compaction degrees under the conditions of our experiment. Heilman (1981) tested root penetration of Douglas-fir seedling into soil (sandy loam and loam) with different bulk densities. He found that bulk densities of 1.74 to 1.83 g/cm^3 (0.998 to 1.05 oz/in^3) prevented root penetration. Lowerts and Stone (1982) tested *Liquidambar styraciflua* seedling growth on plots with different bulk densities. They found the best growth occured on the plots with a bulk density of less than 1.7 g/cm^3 (0.06 lb/in^3) in the top 39 cm (15.4 in) of soil. The potential of *A. rubrum* and *Q. velutina* trees to penetrate compacted soils is demonstrated in the present study, but field soils may be stronger and roots may have other avenues for growth (unlike the present study, where all root growth beyond the pine bark core was by necessity into compacted subsoil). Field experiments would also show whether tree roots in a structural soil reservoir would grow into the subsoil in a variety of conditions. This may partly depend on the precipitation and the infiltration rate of the subsoil. Root penetration of compacted soils is highly dependent on soil moisture (Brady and Weil, 1999). Soil moisture may therefore prevent or allow root penetration. Since the containers in this experiment were kept moist, root penetration resistance was never increased by dry soils as may occur to trees growing in the ground. However, subsoils beneath stormwater reservoirs will very likely remain most.

Overall, the root count data show high variability and thus no significant differences. However, it was obvious that roots grew throughout the soil profile, showing the potential of tree root growth to penetrate compacted soils.

Table 2.2) Number of roots per cm^2 of surface area of exposed subsoil. Roots were counted in different layers (see Fig. 2.2) of soils for two species, *Quercus velutina* Lam. and A*cer rubrum* L. that were planted in highly and moderately compacted soils. n=5, numbers in parentheses= SE mean.

	Low bottom	High bottom	Far side	Close side
Oak				
Severe	1.46 (0.18)	1.026 (.15)	1.81 (0.46)	2.22 (0.59)
Moderate	1.22 (0.29)	1.092 (0.19)	2.28 (0.49)	2.54 (0.58)
Maple				
Severe	0.9 (0.69)	1.31 (1.0)	1.29 (0.42)	1.93 (0.58)
Moderate	1.16 (0.06)	0.37 (0.20)	1.3 (0.6)	2.33 (0.76)
	P>t^z			
Oak				
Severe vs. Moderate	0.43	0.87	0.51	0.67
Maple				
Severe vs. Moderate	0.41	0.50	0.996	0.67

^{Z}Contrast P-values calculated by PDIFF within the GLM procedure of SAS. All data were transformed to square roots before statistical analysis.

Conclusion

Results:

1) roots grew into compacted soils

2) root penetration increased infiltration rate

Both species grew beyond the pine bark into the compacted clay loam. Whether tree roots of other species also behave this way needs to be investigated. In a SWMF utilizing structural soil, tree roots would have a much larger penetrable soil volume than in our experiments. In this, case, tree roots might not grow into the subsoil but might rather grow horizontally. In addition, infiltration will be influenced by the depth of the water table. In this experiment, water could easily exit the system through the drainage holes at the bottom of the containers. Field experiments addressing these questions need to be conducted.

Both species increased the infiltration rate by about 63%. Since the root structure of *Q. velutina* Lam. is rather coarse and those of *A. rubrum* L. fine, roots of other tree species may have the same effect on the infiltration rate after root penetration. Further experiments including more species would address this issue. It would also be interesting to track change in infiltration rate as roots began to penetrate the subsoil. The experiment was conducted during the course of a season. A longer field experiment could answer questions beyond the ability of our experiment using newly established, young seedlings in containers.

Overall, roots can increase the infiltration rate of soils, which would consequently lead to faster drainage and greater stormwater capacity of the structural soil reservoir.

Chapter 3: Infiltration Rate Affects Tree Development, Root Distribution, and Water Uptake in Stormwater Reservoirs Constructed with Engineered Tree Soils

Introduction

Urban runoff is a major contributing factor to the pollution of the Chesapeake Bay and other water bodies on the east coast of the United States. Due to land development and the resulting increase in impervious surfaces, rainfall has fewer opportunities to infiltrate into the ground. Instead, this water drains into storm water systems, where it accelerates due to an increase in water volume before it flows into streams and other waterways. This sudden influx of water often leads to extreme fluctuations in water level in these streams, and severe bank erosion frequently occurs. Because impervious surfaces channel water into these systems, ground water recharge is restricted. The natural hydrology of such streams is changed (SMRC, no date) and they frequently run dry during periods of low rainfall and flood during even moderate intensity storms. In addition, water released into streams may contain a great amount of pollutants, such as sediments, oxygen-demanding substances (organic matter), nutrients (phosphorus, nitrogen), toxic substances, bacteria (Dennison, 1996b), viruses, and heavy metals (EPA, 2004a). Urban runoff is one of the top four causes of waterbody pollution (EPA, 2002b; EPA, 2002c; Frederick et al., 2003) and is overall the “Nation's largest source of water quality problems” (EPA, 2004c). Water pollution and stream bank erosion reduce the integrity of aquatic ecosystems, result in unsafe drinking water(EPA, 2004c).

On-site stormwater management can provide greater infiltration opportunities and decrease the amount of urban runoff directed into waterways. However, most systems, such as detention ponds, have large area requirements. This can be challenging, since undeveloped land may be scarce in urban areas. Urbanization is expected to continue at a rapid pace (Cohen, 2004) and with that, pollution. Since the Clean Water Act (CWA, a federal law for the United States) was established with goals to eliminate pollutant discharges by 1985, to provide water quality for wildlife and recreation, and to control nonpoint source pollution ("Federal Water Pollution Control Act," 2002), there is a need for alternative stormwater management techniques.

The objective of this research was to determine whether a stormwater management facility (SWMF) utilizing structural soil and trees is practicable. The basic premise behind such a system was to utilize structural soils beneath necessary construction (such as parking lots, streets, or sidewalks) so that trees can thrive and stormwater can be temporarily stored in the large voids of the structural soil. From the reservoir, the stormwater can slowly infiltrate into the ground and be transpired by the trees or other vegetation with roots in the reservoir.

Structural soils are soil mixes containing a stone component, such as local quarry gravel, and soil (preferably clay loam). For CU® Structural Soil (patent # 5,849,069), developed at Cornell University, Ithaca, NY, USA, the stone to soil ratio is approximately 80:20 by dry weight (Grabosky et al., 2004). The stone component of this soil type forms a lattice, which gives the soil a high load-bearing capacity that meets engineering standards for supporting pavement, yet still offers large voids which can be filled with water, air, or roots (Grabosky et al., 1999).

Trees in urban settings most often have very little penetrable soil volume at their disposal because surrounding soils under sidewalks and streets must be compacted meet engineering requirements for load bearing. Small planting areas and severe soil compaction greatly restrict root growth and prevent many urban trees from attaining their expected size (Day and Bassuk, 1994). This soil compaction can consequently lead to unhealthy trees that drop limbs, which may lead to damaged property, injured pedestrians and consequently costly law suits.

Since tree roots can easily penetrate structural soil, tree health is improved compared to conventional plantings, and urban trees are able to grow to much larger sizes. The resulting larger canopies will intercept considerably more rainfall, and the increased total transpiration should help remove water from the stormwater reservoir. If trees can transpire an appreciable amount of water, the reservoir of structural will be able to hold more stormwater before it reaches full capacity. Species selection and considerations, such as depth of overflow pipes, are therefore of great importance for planners to design an optimal SWMF.

In this proposed system, root growth and exposure to stormwater will likely depend on the infiltration rate of the subsoil. In poorly draining subsoils, the water from rain events may need days or longer to infiltrate. Other soil types may allow the same rain event to infiltrate within hours. Tree reaction to water table duration is species-specific. Roots of many species cannot survive in submerged soils for long periods of time. Even short periods of time can affect plant biology dramatically (Russell, 1977).

This study seeks to determine how trees develop in a SWMF utilizing structural soil and what they can contribute to such system. Questions we would like to answer are:

1) Can trees thrive in fluctuating water tables likely present in our proposed system?
2) How do trees develop in different water table regimes?
3) Do trees grow differently in a system using CU® Structural Soil compared to a mix with Carolina Stalite (a heat-expanded slate) as the stone component?

Material and Methods

Overview and Experimental Design

The experiment was conducted at the Urban Horticulture Center of Virginia Tech in Blacksburg, VA, USA (USDA Hardiness Zone 6a). Between 24 and 26 May 2005 3-yr-old bare-root *Fraxinus pennsylvanica* 'Georgia Gem' and *Quercus bicolor,* (J. Frank Schmidt and Sons Co., Boring, OR) were planted in 94.6 L containers. Two kinds of structural soil were used as substrate for one species, *F. pennsylvanica*: CU® Structural Soil and a mix with Carolina Stalite (Carolina Stalite Company, Salisbury, NC), a heat-expanded slate, as the stone component. The StaliteMix was used for both species and the CU® Soil was used in addition for the *F. pennsylvanica* 'Georgia Gem' only, to compare the substrate types. The containers were treated with SpinOut®, a copper hydroxide paint (Griffin LLC, Valdosta, GA, USA) to keep roots in the interior of the container. After planting, trees were irrigated daily for two months to promote establishment before starting water table treatments. Trees were subjected to different simulated water tables, starting on 27 July 2006, that mimicked rapid, moderate, and slow soil infiltration rates (2 cm/hr, 1 cm/hr, and 0.1 cm/hr; 0.79, 0.39, and 0.039 in/hr). Simulated water tables were created with a series of valves installed in the container sidewalls that allowed the pots to be drained to a particular level. Rainfall was excluded and evaporation from the substrate surface prevented by means of a tightly fitting white plastic covering over the top of the container. Transpiration rate, sap flow, leaf area, root distribution and dry weights were measured (see below).

Treatments were assigned in a completely random experimental design with five replications: [1 tree species X two soils + 3 tree species X one soil (CU® Structural Soil)] X 3 flooding regimes X 5 replications = 75 total trees. Containers were placed 30 cm (11.8 in) apart in two rows with 60-cm (23.6-in) distance between rows.

All data, unless specified otherwise, were analyzed by analysis of variance within the GLM procedure of SAS (SAS, vers. 9, SAS Institute, Cary, NC).

Container Preparation and Treatments

All interior sidewalls and container bottoms were painted with two coats of SpinOut® (Griffin LLC, Valdosta, GA, USA) to prevent circling roots. To allow standardized lowering of the water table, we inserted vinyl tubing (I.D. 1.59 cm; 0.625 in) into the container side as close to the bottom as possible and connected another tube vertically with the same height as the container, using polypropylene insert tees. The end of the tube that was inserted into the container was wrapped with window screening to prevent washing out of soil or stones and clogging of the tubes. The vertical vinyl tubing, depending on the treatment, had outlets at certain heights, to allow lowering the water table to the desired level. Tubing was crimped with a PVC ring to create a valve that could be closed to fill up the container or opened to allow drainage. The bottom outlet allowed complete drainage of the container (Fig. 3.1.). All water table adjustments (pots filled and valves opened or closed according to the protocol) occurred between 0900 and 1200 HR on appropriate days. The treatment was suspended for winter and the containers were wrapped with insulation on 27 Oct to avoid winter damage. During the winter months, the containers were periodically irrigated so that container media was kept moist. Insulation was taken off on 17 April and the treatments were applied again until the date of harvest for the particular species in Sept. of 2006.

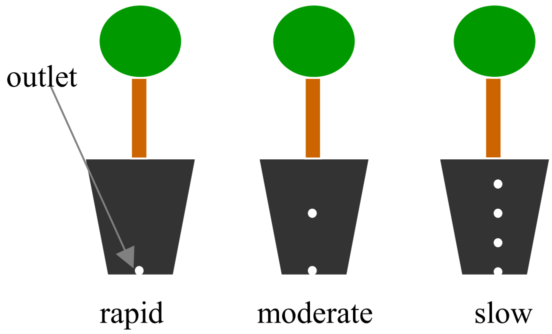

Figure 3.1) Sketch of containers for each treatment, with outlets, to simulate rapid, moderate, and slow infiltration rate of soils.

Rapid infiltration rate treatment (2 cm/hr; 0.79 in) had a bottom outlet but no additional outlet. Containers were filled up on day 1 and completely emptied out on day 2, followed by filling up on day 3.

Moderate infiltration rate treatment (1 cm/hr; 0.39 in) had a bottom outlet and an outlet at mid container height (24 cm [9.45 in] from top). Containers were filled up on day 1, emptied half way on day 2, emptied completely on day 3, and were filled back up on day 4.

Slow infiltration rate treatment (0.1 cm/hr; 0.039 in) had a bottom outlet and four additional outlets at 10-cm intervals. Containers were filled up on day 1, lowered 10 cm (3.9 in) every five days, until the container was completely emptied out on day 25.

Soil Preparation

For both types of structural soil were mixed with a small electrically powered cement mixer according to specifications as follows:

CU® Structural Soil:

The recommended stone to soil ratio of this mix is 80:20 by dry weight, and the suggested soil type is clay-loam. A hydrogel (Viterra® Gelscape®, Amereq, Inc., New City, NY) (0.03%) is added to bind the soil to the stone to avoid downward movement (settling) of the clay-loam soil (Costello and Jones, 2003). The soil we used was a clay-loam consisting of 25.9% sand, 36.9% silt, and 37.2% clay with a dry weight of

0.99 kg/L (8.23 lb/gal). With the gravel (local quarry lime-stone) having 1.52 kg/L (12.6 lb/gal) dry weight, the recipe for the 80:20 ratio would have been 23.3 L (6.16 gal) gravel per 3.8 L (1 gal) soil. To simplify the process we mixed 22.7 L (6 gal) of gravel with 3.8 L (1 gal) of soil, which resulted in 78:22 ratio and resulted in: 113.6 L (30 gal) gravel + 30 g (1.1 oz) hydrogel + 9.5 L (2.5 gal) soil.

Process: Gravel was loaded into a small, electrically powered cement mixer. While running, the gravel was wetted and the hydrogel (that had been previously mixed into a slurry) was added. Soil was then added and mixed in. The mixture was then transferred to each growing container and with a tree in place. Careful attention was made not to over mix the soil to assure the clay loam soil did not settle out.

Carolina Stalite-Mix:

Stalite is a heat-expanded slate produced by Carolina Stalite Company, Salisbury, NC. The recommended soil for the Stalite mix is a sandy clay loam, mixed to a stone:soil ratio of 80:20 by weight (Costello and Jones, 2003). The soil we used was a mix of topsoil, clay loam (35.6% sand, 49.8% silt, and 14.6% clay), and sand (3:1:1), resulting in 39.9% sand, 27.8% silt, and 32.3% clay. The soil dry weight was 0.98 $kg \cdot L^{-1}$ (8.1 lb/gal) and that of Stalite was 0.76 $kg \cdot L^{-1}$ (6.3 lb/gal). This resulted in a ratio of 19.4 L (5.1 gal) Stalite for 3.79 L (1 gal) of soil to achieve the recommended ratio of 80:20. Again, for ease of mixing we rounded off to 18.9 L (5 gal) Stalite: 3.79 L (1 gal) soil, giving a ratio of 78:22, which is within the acceptable range. Because of the porous structure of the Stalite, a hydrogel was not needed to keep the soil from settling to the bottom of the system during mixing.

Process: Stalite was loaded into the circulating cement mixer. The Stalite was wetted and 9.5 L (2.5 gal) of the soil mix was added.

Transpiration Rate

Transpiration rates (LiCor 1600 Steady State Porometer; LI-COR Biosciences, Lincoln, NE) of *F. pennsylvanica* and *Q. bicolor* were measured periodically during the 2006 growing season. To capture whole-day transpiration rates we took measurements every two hours during daylight hours, starting at 0800 and finishing at 1800 HR. The measurement dates were spread over the summer months, with 12 measurement dates between May and September (09, 10, and 12 May; 10, 12, 17, 18, 19, 24, and 31 July; 01 Aug; and 11 Sept 2006). One measurement per tree was made on the third to fifth leaf from the tip of a randomly selected sunlit branch. For compound leaves we measured the apical leaflet.

Sap Flow

Two to three trees per species X substrate combination were randomly selected among those within reach of the sap flow gauge cables, and sap flow was logged for eight consecutive days for each of the species X substrate. The gauges were set up on 5 Sept for *F. pennsylvanica* in the Stalite mix, on 14 Sept for *F. pennsylvanica* in CU® Structural Soil, and on 23 Sept 2006 for *Q. bicolor.* The measurements were conducted using a heat-balance sap flow system (Flow 32-AO Sap Flow Measurement System, Dynamax, Houston, TX) (Steinberg et al., 1989). One gauge was fitted around the main trunk with an insulated collar, a heat shield around the gauge, and an aluminum foil wrap as radiation protection. The gauges had certain trunk diameter intervals for which the particular gauge was suitable for (15-19 mm [0.59-0.75 in], and 24-32 mm [0.94-1.26 in]). Depending upon the trunk diameter and the branching of the tree, limbs may have been below the gauge. The leaves from these branches were excluded from the gauge-specific leaf area measurements and thus from the sap flow rate per cm^2 leaf area. Data were collected with a datalogger (CR10, Campbell Scientific, Logan, Utah) every 60 s, averaged every 15 min, recorded every 30 min, and given as a rate per hour. These rates were then combined with leaf area data to calculate the sap flow per cm^2 leaf area.

Leaf Area

Leaf area was measured on subsamples of *F. pennsylvanica* and *Q. bicolor* to estimate whole-tree transpiration and to standardize sap flow data to a per-leaf-area basis. Leaves were collected separately for the branches above and below the sap flow gauges just after completion of the sap flow measurements. Leaf area of subsample groups of 10, 20, 30, 50, 65, 80, 100 leaves for *F. pennsylvanica*, and 5, 10, 20, 30, 40, 60, 80 leaves for *Q. bicolor*, respectively, was measured with a Li-Cor 3000 (Li-Cor Biosciences, Lincoln, NE). Each subsample was then dried to a constant weight at 50°C. The leaf area:dry weight relationship was then determined by linear regression (SigmaPlot, vers. 9.01, SYSTAT Software Inc., San Jose, CA). All other leaves were then dried to a constant weight at 50°C (122ºF). Total tree leaf area and leaf area above all sap flow gauges were then estimated after determination of dry weight.

Shoot and Root Dry Weight

Trunk diameter was measured at 30 cm (11.8 in) above the soil before cutting the shoot at the soil line. Shoots and roots were dried to a constant weight at 50ºC (122ºF). The older roots, diameter > 1 cm (0.39 in), were divided from the younger, finer roots, < 1 cm (0.39 in), to determine the root growth during the treatment.

Root Size and Distribution

All containers were laid on their sides, and trees were gently removed between 18 Sept and 7 Oct 2006, starting with *F. pennsylvanica* in Stalite, then the same species in gravel, and then *Q. bicolor*. The width (in two perpendicular directions) and depth of the live root system was measured before washing the stones and soil from the root system, and the mean for the two directions was considered to be the root system width. To maintain the same relative distance to the water table levels, the depth was measured from the point on the trunk that was at the same height as the container edge. All root systems were then dried to a constant weight at 50ºC (122ºF).

Results and Discussion

Tree Development

Overall, all trees visually developed well in both structural soils and in all three fluctuating water table treatments. There was strong evidence that shoot, total root, new root, and total dry weights were higher for the *F. pennsylvanica* trees in the moderate infiltration treatment than for those exposed to rapid or slow infiltration rates (Table 3.1. and 3.2.). For *Q. bicolor,* shoot and total dry weights were highest for trees in moderate infiltration treatments. There was strong evidence that the trunk diameter of *Q. bicolor* was greatest for trees in the moderate infiltration treatment, followed by those exposed to rapid infiltration, and lowest for the trees in the slow infiltrated soils. Overall best development of *Q. bicolor* was therefore in the moderate infiltration treatment.

Table 3.1) Mean dry weight of roots and shoots, root:shoot ratio, and trunk diameter for *Quercus bicolor* Willd.(swamp white oak) and F*raxinus pennsylvanica* Marsh. (ash) grown for two growing seasons in fluctuating water tables according to slow, moderate, and rapid infiltration rate of subsoils. Ash was grown in two soil types. n=5. Numbers in parentheses= SE mean.

Rapid Infiltration	Root (g)	Shoot (g)	Total (g)	New Roots [z] (g)	Root/Shoot	Trunk Diameter (mm)
Ash Stalite	525.16 (121.8)	1105.24 (172.9)	1630.4 (292.5)	168.34 (47.5)	0.46 (0.03)	37.24 (1.2)
Ash Gravel	475.3 (73.9)	991.6 (165.9)	1466.9 (224.6)	176.1 (34.3)	0.51 (0.1)	34.79 (2.9)
Swamp White Oak	348.38 (33.5)	622.6 (98.1)	970.98 (110.4)	84.46 (15.0)	0.6 (0.1)	26.5 (5.8)
Moderate Infiltration						
Ash Stalite	672.32 (70.2)	1183.34 (118.8)	1855.66 (181.2)	234.4 (27.7)	0.57 (0.03)	35.88 (2.3)
Ash Gravel	568.02 (101.5)	1240 (244.0)	1808.06 (326.3)	220.34 (62.4)	0.488 (0.1)	36.26 (3.1)
Swamp White Oak	455.28 (61.7)	944.83 (168.0)	1400.1 (228.2)	164.83 (10.4)	0.49 (0.02)	33.25 (1.7)
Slow Infiltration						
Ash Stalite	441.58 (23.1)	763.18 (38.8)	1204.8 (27)	108.66 (17.1)	0.59 (0.1)	32.43 (1.5)
Ash Gravel	457.9 (97.3)	825.38 (166.2)	1283.3 (250.6)	123.7 (45.1)	0.572 (0.1)	32.99 (1.2)
Swamp White Oak	364.46 (87.3)	421.1 (141.02)	785.56 (221.0)	131.36 (52.2)	0.96 (0.2)	18.75 (1.7)

[z] New roots are roots that are less than 1 cm in diameter

Table 3. 2) *P*-values for treatment effects on roots and shoots, root:shoot ratio, and trunk diameter for *Quercus bicolor* Willd. (swamp white oak) and F*raxinus pennsylvanica* Marsh.(green ash) grown for two growing seasons in fluctuating water tables according to slow, moderate, and rapid infiltration rate of subsoils. Ash was grown in two soil types. n=5.

	$P > t^z$					
Ash Gravel	Root	Shoot	Total	New roots	Root/Shoot	Trunk Diameter
Rapid vs. Moderate	0.459	0.293	0.320	0.460	0.799	0.640
Moderate vs. Slow	0.380	0.085	0.131	0.114	0.335	0.304
Slow vs. Rapid	0.889	0.479	0.590	0.384	0.475	0.568
Ash Stalite						
Rapid vs. Moderate	0.244	0.738	0.509	0.273	0.218	0.666
Moderate vs. Slow	0.073	0.815	0.065	0.043	0.799	0.279
Slow vs. Rapid	0.504	0.152	0.218	0.320	0.141	0.135
Swamp White Oak						
Rapid vs. Moderate	0.280	0.130	0.140	0.134	0.520	0.012
Moderate vs. Slow	0.360	0.021	0.047	0.514	0.017	0.001
Slow vs. Rapid	0.860	0.290	0.490	0.338	0.043	0.004

^{z}Contrast *P*-values were calculated by PDIFF within the GLM procedure of SAS.

The root/shoot ratio (rs) for *Q. bicolor* in the slow infiltration rate containers was highest. The root/shoot ratio is important because it indicates the potential of the plant to absorb water according to the transpiration rate. If the ratio of area of absorbing surface to area of transpiring surface (i.e. rs), is too low, absorption might lag behind transpiration, leading to leaf water deficits (Kozlowski and Pallardy, 1997). A high rs is common for stressed trees (Zwack et al., 1999) indicating that shoot development may be more affected by high water tables than root systems.

In general, this study provided evidence that trees in moderately drained soils develop best compared to those with rapid or slow simulated drainage rates. De Andrade et al. (1999) tested flooding effects on root and leaf dry weight, root/shoot ratio, and height of two lowland species, *Cytharexyllum myrianthum* Cham. and *Genipa Americana* L., and found that one species, *G. americana,* showed reduced root and leaf dry weight, root/shoot ratio, and height, whereas *C. myrianthum* showed the opposite reaction. Likewise, the two species studied here reacted differently to flooded soils.

The root distribution (width and depth) data for *F. pennsylvanica* showed strong evidence that trees in the Stalite mix grew wider than those in the CU® Structural Soil and the root depth depended on the infiltration treatment and on the type of substrate (Tables 3.3. to 3.5.). This may mean that CU® Structural soil, which uses rather angular limestone, interlocks more tightly, leading to a stronger overall soil matrix than the Stalite mix, which has more oval-shaped stones. Perhaps roots were better able to push the Stalite mix aside at the structural soil/container interface. We also observed that trees in the Stalite mix were easily removed from the substrate, even when root systems were extensive. This suggests that further research concerning the stability of trees in the Stalite mix may be of interest to avoid tree failure and its consequences. The depth of the root systems exhibited a treatment x substrate interaction. Separating the soil types, *F. pennsylvanic*a trees in the gravel mix grew deepest in the rapid infiltration treatment compared to trees in moderate or slow infiltration soils. Trees in the Stalite mix did best in the rapid infiltration rate, followed by those in moderate and last slow infiltration treatments.

Table 3.3) Mean rootball depth (maximum possible = 47 cm) and width (maximum possible = 53.3 cm) and treatment comparisons for *Quercus bicolor* Willd. (Swamp white oak) subjected to three simulated drainage regimes..

	Drainage Regime		
	Rapid (cm)	Slow (cm)	Moderate (cm)
Depth	43.7 (0.41)[z]	36.1 (0.58)	32.7 (0.31)
Width	41.7 (1.43)	40.1 (2.71)	53.3 (0.00)

	$P > t^y$
Depth	
Rapid vs. Slow	0.001
Rapid vs. Moderate	0.001
Slow vs. Moderate	0.077
Width	
Rapid vs. Slow	0.823
Rapid vs. Moderate	0.125
Slow vs. Moderate	0.088

[z]Number in parentheses = SE mean. n=5.
[y]Contrast *P*-values were calculated by PDIFF within the GLM procedure of SAS.

Table 3.4) Mean rootball depth (maximum possible = 47 cm) and width (maximum possible = 53.3 cm) of *Fraxinus pennsylvanica* Marsh. (green ash) grown in gravel- or Stalite-based structural soil and subjected to three simulated drainage regimes.

	Drainage Regime		
	Rapid (cm)	Slow (cm)	Moderate (cm)
Gravel			
Depth	46.0 (0.40)[z]	38.1 (0.32)	38.6 (0.37)
Width	41.7 (1.25	39.4 (0.74)	43.2 (1.76)
Stalite			
Depth	47.0 (0.00)	33.3 (0.56)	41.7 (0.91)
Width	51.3 (0.49)	46.5 (0.86)	50.5 (0.71)

[z]Number in parentheses = SE mean. n = 5.

Table 3.5) *P*-values from analysis of variance for rootball depth (maximum possible = 47 cm) and width (maximum possible = 53.3 cm) for *Fraxinus pennsylvanica* Marsh. (green ash) grown in gravel- or Stalite-based structural soil and subjected to three simulated drainage regimes.

	Depth	Width
	$P > F$	
Drainage	0.001	0.289
Substrate	0.813	0.001
Drainage X substrate	0.015	0.874
Contrasts	$P > t^z$	
Gravel vs. Stalite	NA	0.001
Gravel		
Rapid vs. Slow	0.001	NA
Rapid vs. Moderate	0.001	NA
Slow vs. Moderate	0.783	NA
Stalite		
Rapid vs. Slow	0.001	NA
Rapid vs. Moderate	0.007	NA
Slow vs. Moderate	0.001	NA

^{z}Contrast *P*-values were calculated by PDIFF within the GLM procedure of SAS.

There was evidence that the roots of *Q. bicolor* grew wider for trees in the moderate infiltrated soils than in the slow infiltration treatment. The depth was highly treatment dependent. Trees in the rapid infiltration treatment grew deeper than those in slow or moderately infiltrated soils, the latter being the most shallow. Although a root system may have a smaller distribution, the absorptive surface may be equal or even greater than for a root system that is wider and deeper. The water uptake depends on the area of absorptive surface, not necessarily on the distribution. The distribution may influence the tolerance to drought since a greater soil volume is explored and thus more water can be extracted. *Q. bicolor* trees seem to be able to cope with conditions that are suboptimal for other tree species, submerged soils or soils with low water content. However, they may still grow best in rather medium wet soils. On the other hand, if the soil water supply is inadequate and soils dried out, trees might be exposed to drought even when the root system is extensive.

The species used in this study are both bottomland trees, normally found along edges of streams and therefore in rather wet soils. However, *F. pennsylvanica* prefers well drained, fertile soils, whereas *Q. bicolor* seems to be more tolerant to wet soils (Burns and Honkala, 1990). We selected these species because of their tolerance for wet conditions as well as neutral to high soil pH, but their level of tolerance might be different. Further research needs to be done to determine the response of different bottom and upland species to fluctuating water tables. We only used one species in two different structural soils so we were not able to explore the interaction between species and substrate. There is evidence, however, that substrates affect tree growth. This suggests that further research might be useful to determine if particular substrates are better suited to particular conditions and species. Overall, these results showed that trees thrive in the system, and we therefore conclude that a stormwater management facility utilizing structural soil and trees can serve as a system to process stormwater on-site without occupying much surface. In addition to the general benefits of large trees to human well being, wildlife, and the environment they have the potential of contributing to the system through e.g. water uptake.

Water Relations

Sap flow measurements indicated that the trees in our experiment transpired between 400 and 1280 g/day/m^2 (1.34-4.28 oz/day/ft^2) (Table 3.6 to 3.8). This is within the range of the findings from Kramer and Kozlowski (1960), who summarized transpiration rates for *Pinus taeda*, *Liriodendron tulipifera*, and *Quercus rubra* seedlings of 508, 976, and 1245 g/day/m^2 (1.7, 3.3, and 4.2 oz/day/ft^2), respectively (quoted in (Kozlowski and Pallardy, 1997).

Since the sap flow of the two tree species in our experiments was measured at different times, a species comparison would have little informational value because the transpiration, and thus sap flow, depends on factors such as temperature and relative humidity. Results for *F. pennsylvanica* showed no evidence that the substrate or the treatment had an effect on the sap flow. However, there is strong evidence that the treatment had an effect on the transpiration rate (per leaf area) of *Q. bicolor* trees, showing a higher value for trees in the slow infiltration treatment compared to the moderate and rapid infiltration containers (table 3.6 to 3.8). Between the moderate infiltration rate and the rapid infiltration rate, the data showed strong evidence that the trees exposed to the moderate infiltration regime transpired more water. This means that the trees exposed to the longest flooding regime had the highest transpiration rate (per leaf area). This may indicate that the trees became adapted to inundated root zones, since stomatal closure is typically a reaction of trees to flooded soils (Kozlowski and Pallardy, 1997; Mengel and Kirkby, 2001). Closed stomata prevent transpiration to a great extent (Kozlowski and Pallardy, 1997). For example, European silver birch transpire 1.2 $mmol \cdot m^{-2} \cdot s^{-1}$ with open stomata, but only 0.15 $mmol \cdot m^{-2} \cdot s^{-1}$ when the stomata are closed; European beech transpires about four times as much water with open stomata (Larcher, 1975 in Kozlowski, 1997 #188). *Q. bicolor* trees are fast growing and they tolerate flooding (Burns and Honkala, 1990). This could explain the rapid transpiration rate of the trees that were exposed to flooding the longest periods of time. When comparing the daily rate and total amount of water transported through the trees (Table 3.6-3.8.), we found that, for *Q. bicolor*, the daily rate was highest for the trees in slowly drained soils, but the total daily volume was highest for the trees exposed to the moderate infiltration treatment, a direct result of their larger stature. The moderate infiltration treatment also resulted in the highest daily volume of water being transported through the plant for *F. pennsylvanica* in gravel. Therefore, in addition to transpiration rate, the size of the tree is an equally important consideration when determining the total amount of water that can be removed from the reservoir. There was no evidence for any differences in total sap flow among treatments for *F. pennsylvanica* in the Stalite mix.

Table 3.6) Daily rate and volume of sap flow of *Fraxinus pennsylvanica* Marsh. (green ash) in engineered soils with Stalite base and subjected to three simulated infiltration rates.

Infiltration	Daily rate[z] (g/day/cm^2)	Daily volume (liter)
Rapid[y]	0.091 (0.025)	1.07 (0.07)
Moderate	0.042 (0.008)	0.96 (0.32)
Slow	0.069 (0.015)	0.83 (0.07)
	P > t[x]	
Rapid vs. Moderate	0.136	0.671
Rapid vs. Slow	0.421	0.330
Moderate vs. Slow	0.316	0.576

[z]Daily rates are the per day mean of flow measured 5-13 Sept. 2006. Numbers in parentheses are SE of means.
[y]n= 2,2, and 3 for rapid, moderate and slow infiltration, respectively.
[x]Contrast *P*-values were calculated with the PDIFF technique within the GLM procedure of SAS.

Table 3.7) Daily sap flow rate and volume for *Fraxinus pennsylvanica* Marsh. (green ash) in engineered soils with gravel base and subjected to three simulated infiltration rates.

Infiltration	Daily rate[z] (g/day/cm^2)	Daily volume (liter)
Rapid[y]	0.092 (0.017)	1.24 (0.21)
Moderate	0.069 (0.003)	2.14 (0.28)
Slow	0.109 (0.026)	1.55 (0.50)
	$P > t$[x]	
Rapid vs. Moderate	0.307	0.080
Rapid vs. Slow	0.500	0.534
Moderate vs. Slow	0.142	0.254

[z]Daily rates are the per day mean of flow measured 14-22 Sept 2006. Numbers in parentheses are SE of means.
[y]n= 3,3, and 2 for rapid, moderate and slow infiltration, respectively.
[x]Contrasts were calculated with the PDIFF technique within the GLM procedure of SAS.

Table 3.8) Daily rate and volume of sap flow of *Quercus bicolor* Willd. (Swamp white oak) in engineered soils with Stalite base and subjected to three simulated infiltration rates.

Infiltration	Daily rate[z] ($g/day/cm^2$)	Daily volume (liter)
Rapid[y]	0.058 (0.01)	0.58 (0.03)
Moderate	0.075 (0.01)	1.57 (0.11)
Slow	0.128 (0.04)	0.96 (0.51)
	$P > t$[x]	
Rapid vs. Moderate	0.511	0.016
Rapid vs. Slow	0.044	0.283
Moderate vs. Slow	0.096	0.104

[z]Daily rates are the per day mean of flow measured 23 Sept. - 1 Oct. 2006. Numbers in parentheses are SE of means.
[y]n= 3,3, and 2 for rapid, moderate and slow infiltration, respectively.
[x]Contrast *P*-values were calculated with the PDIFF technique within the GLM procedure of SAS.

The porometer data (means in Fig. 3.2. for *Q. bicolor* and 3.3. for *F. pennsylvanica*) showed evidence that trees in the slow infiltration containers transpired less than the ones exposed to the moderate or rapid infiltration treatment. This disagrees with the findings from our sap flow measurements. Ansley et al. (1994) compared both methods in their work and found that both methods are comparable. In addition, we conducted porometer and sap flow measurements on the same trees at the same time on 11 Sept for *F. pennsylvanica* in the Stalite mix, on 20 Sept for the same species in the gravel mix, and on 26 Sept for *Q. bicolor* (Table 3.10) and patterns of water use indicated by both measurement techniques were similar. However, there are no significant differences between the treatments for either measurement method, sap flow gauge or porometer, on these three days. Therefore, we believe the differences between overall porometer and sap flow measurements are related to the different times of year and/or drainage stage of individual treatments at the measurement time. The porometer measurements were conducted on 12 days, all through the summer, starting in May and ending in September.

We present a composite measurement in Figure 3.2 and 3.3 (each data point is the average of 72 measurements (6 measurements per day X 12 days). The sap flow measurements were taken throughout an 8-day period in September, right before harvestings the leaves. The sap flow measurements therefore capture transpiration at a particular time of year, but include a longer portion of the drainage cycles represented by each treatment. In addition, although sap flow measures whole tree water use, we were only able to place gauges on two to three replications at one time due to technical limitations.

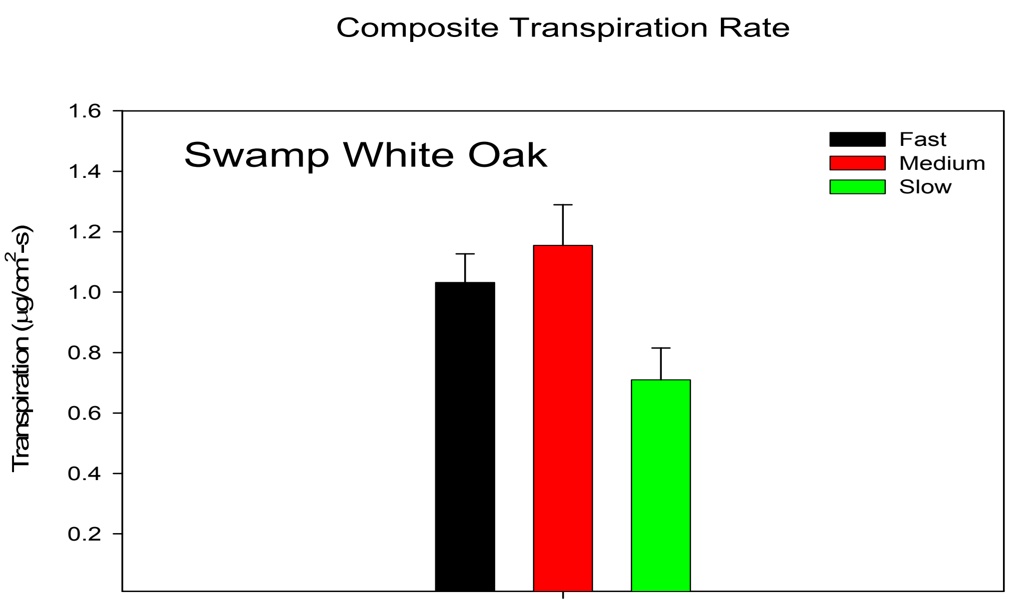

Figure 3.2) Mean transpiration rates of *Quercus bicolor* Willd. (swamp white oak) subjected to three drainage regimes. Bars represent standard error of the mean. n = 5. Each replication is the mean of diurnal (=6) measurements taken over 12 days in May -Sept. 2006 (= 72 total). See Table 3.9 for statistics.

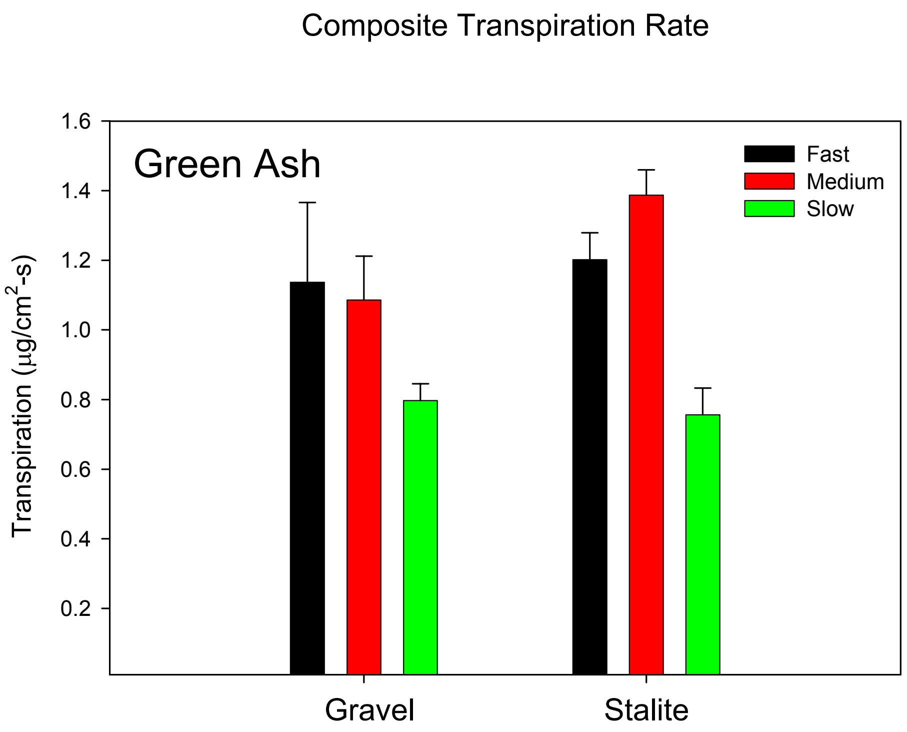

Figure 3.3) Mean transpiration rates of *Fraxinus pennsylvanica* Marsh. (green ash) and Q*uercus bicolor* Willd. (swamp white oak) grown in engineered soils with gravel or Stalite base and subjected to three drainage regimes. Bars represent standard error of the mean. n = 5. Each replication is the mean of diurnal (= 6) measurements taken over 12 days in May -Sept. 2006 (= 72 total). See Table 3.9 for statistics.

Table 3.9) *P*-values from analysis of variance for composite transpiration rates of *Fraxinus pennsylvanica* Marsh. (green ash) and *Quercus bicolor* Willd. (swamp white oak) grown in two engineered soils and subjected to three drainage regimes.

	P > F	
	Green Ash	Swamp White Oak
Substrate	0.282[z]	NA[y]
Drainage	0.002	0.040
Substrate X drainage	0.366	NA
	P > t[x]	
Contrasts		
Fast vs. Medium	0.585	0.455
Fast vs. Slow	0.003	0.054
Medium vs. Slow	0.001	0.017

[z]n = 5. Each replication is the mean of diurnal (=6) measurements taken over 12 days in May -Sept. 2006 (= 72 total).
[y]Swamp white oak was grown in one substrate only.
[x]Contrast *P*-values were calculated with the PDIFF technique within the GLM procedure of SAS.

Table 3.10) Treatment comparisons of water use rate by sap flow meter (sap flow) and porometer (transpiration) for *Fraxinus pennsylvanica* Marsh. (green ash) in engineered soils with Stalite base on 11 Sept 2000, green ash in engineered soils with gravel base on 20 Sept and *Quercus bicolor* Willd. (swamp white oak) in engineered soils with Stalite base on 26 Sept, all subjected to three simulated drainage regimes.

	Green Ash/Stalite (11 Sept)	Green Ash/Gravel (20 Sept)	Swamp White Oak (26 Sept)
Sap flow ($g/cm^2/day$)			
Rapid	0.078 (0.017)[z]	0.062 (0.011)[y]	0.099 (0.029)[x]
Moderate	0.045 (0.013)	0.057 (0.005)	0.084 (0.012)
Slow	0.065 (0.0080	0.088 (0.006)	0.118 (0.027)
Transpiration ($\mu g/cm^2/s$)			
Rapid	1.036 (0.111)[w]	0.398 (0.065)	0.340 (0.130)
Moderate	0.850 (0.145)	0.380 (0.039)	0.522 (0.216)
Slow	0.549 (0.099)	0.400 (0.057)	0.754 (0.167)
		$P > t$[v]	
Sap flow			
Rapid vs. Moderate	0.130	0.658	0.648
Rapid vs. Slow	0.486	0.094	0.607
Moderate vs. Slow	0.259	0.057	0.371
Transpiration			
Rapid vs. Moderate	0.294	0.824	0.473
Rapid vs. Slow	0.014	0.974	0.099
Moderate vs. Slow	0.101	0.799	0.361

[z]Numbers in parentheses are SE of means. n= 2, 3, and 2 for rapid, moderate and slow infiltration, respectively. n= 3, 2, and 3 for rapid, moderate and slow infiltration, respectively.
[y]n= 2,2, and 3 for rapid, moderate and slow infiltration, respectively.
[x]n= 3,2, and 3 for rapid, moderate and slow infiltration, respectively.
[w]n=5
[v]Contrast *P*-values were calculated with the PDIFF technique within the GLM procedure of SAS.

Overall, our measurements resulted in reasonable transpiration rates for this size tree. The data also show that, depending on the size, an individual tree can take up more total water than other trees with higher transpiration rates. Since trees have the potential to grow very large in structural soil, this can be a great amount of water. Large deciduous trees are capable of transpiring 300 L (79.3 gal) per summer day (Thomas, 2000). Therefore, depending on the design of the SWMF utilizing structural soil, size and number of trees can be a great contributor to the system and can potentially increase the capacity of the reservoir through water uptake. However, even if the water uptake of the trees is minor, rainfall interception can still play a significant role in stormwater mitigation. The canopy of large trees has been shown to intercept 80% of the rainfall, whereas small trees may only intercept 16% (Xiao and McPherson, 2003). This may greatly decrease the amount of runoff because less water reaches the ground. This leads to the conclusion that our proposed system would be a suitable way to collect stormwater, occupying no additional space, and providing the benefits of large trees.

Conclusions

It has been clearly demonstrated that structural soil can dramatically improve tree growth and quality compared to trees growing in conventional urban soils. Trees in our experiments were exposed to extreme water conditions to determine tree development and contribution to a stormwater management system utilizing these two components: trees and structural soil. Results show that:

1) trees thrive in a system with structural soil and fluctuating water tables
2) fluctuating water tables have an impact on tree development
3) the structural soil type appears to have an impact on root distribution
4) trees in such a system take up water within the normal range

F. pennsylvanica and *bicolor* grew well in the structural soil with fluctuating water tables. There were differences in tree development and root distribution, but our data indicated high variation. We therefore recommend further research to clearly determine tree development in such systems for a variety of species. Since our experiments were container experiments, field experiments would be of great value. We used infiltration data from the literature, but the critical question would be how the overall subsoil below the structural soil reservoir actually drains. Infiltration tests of a specific spot may show a very slow infiltration rate, but the chance of alternative pathways for water, such as cracks, is high. This would lead to a high overall infiltration rate of the subsoil. It may be difficult to determine the infiltration rate of the soil below the reservoir without testing it for the entire area. The overall infiltration rate and the precipitation in the particular area would determine how well the trees thrive and how well the root system will be distributed. Infiltration and precipitation rate would greatly influence the water uptake by the tree. The trees in our experiment transpired a reasonable amount of water. It would be useful to determine how much water a tree transpires in such system at different ages. Considering that trees show increased growth in structural soil compared to conventional tree plantings in urban settings, trees may transpire at above-average rates for urban trees.

The species we used were both bottomland species which are tolerant of wet soils. Future experiments involving a greater variety of trees would broaden our knowledge about tree behavior in a structural soil reservoir for stormwater management. More experiments utilizing different kinds of structural soils would help to determine whether the differences in substrates affect tree and root development. Our data showed an influence of the substrate on root distribution, but since these were container experiments, field experiments would be useful for confirming these influences.

Overall, trees grew well and there is a great potential for a structural soil reservoir incorporating trees to be useful as a stormwater management tool. This could decrease runoff and thus improve the quality of water bodies. Likely candidates for tree species selection include mostly deciduous species for much of the United States. Contribution to stormwater removal by transpiration will be slight when trees are dormant, although contribution to drainage from roots growing into the subsoil could still be substantial (Chapter 2). Even if trees would not contribute at all to the system by water uptake, large trees and their benefits, such as rainfall interception, improvement of air quality, energy savings, improvement of human well being and wildlife conditions, would improve the urban environment immensely.

Chapter 4: Summary and Conclusions

All trees grew well in structural soil with fluctuating water tables such as would likely be found in a storm water management system utilizing structural soil as a stormwater reservoir. The fact that trees in this study thrived under the various water table regimes is significant because even without a substantial role in emptying stormwater from the reservoir, our data indicate that successful urban tree plantings and stormwater management can be achieved in one system. In fact, we have shown that transpiration rate is normal under most conditions and that tree roots can aid infiltration into subsoil below the reservoir. Trees therefore will actually make direct contributions to stormwater removal in addition to the significant stormwater abatement benefits normally provided by large urban trees.

Subsoil and structural soil interactions influencing performance of the system

We evaluated two kinds of structural soil, CU® Structural soil and a mix with Stalite. Both have a porosity of more than 30%. When designing a reservoir with structural soil, the precipitation of the particular area needs to be taken into account for designing a suitable capacity. For example, a 100-yr storm with 24-hr duration for Blacksburg, VA and Raleigh, NC is 165 mm (6.5 in) and 194 mm (7.6 in), respectively (NWS, 2006). For Blacksburg, a 49.5 cm-deep (19.5 in) stormwater reservoir would be needed despite the addition of trees. To provide management at all times and to prevent pavement failure, there should be a buffer zone below the pavement and an overflow pipe.

In addition, our studies indicate that if water is allowed to stand in the reservoir for long periods of time, rooting depth may be restricted, depending upon the species and the structural soil. We found for *F. pennsylvanica* and *Q. bicolor* that root systems of trees in soils with a slow infiltration rate (therefore submerged soils) were shallower compared to those in well drained soils. *Fraxinus pennsylvanica* and *Q. bicolor* in containers simulating slow subsoil infiltration rates grew a shallower root system, 24% and 17%, respectively than trees in the rapidly draining treatment. This may be different for other species since both species in our experiment are bottomland species, but overall it suggests that trees grow a more evenly distributed root system in well drained soils. Clearly, trees root systems develop fully and extend to the bottom of the reservoir if drainage rates result in roots being submerged for 24 h or less. Tree root depth was limited in slower draining systems although the largest trees were those drained over a three day period (moderate drainage). Exactly how long roots can remain submerged for various species, the long-term effects of restricted rooting depth, and the effects of standing water during the dormant season (when we suspended drainage treatments for our experiments) still need to be determined. In sum, the infiltration rate of the subsoil, local precipitation patterns, and tree rooting needs will determine the optimal depth for placement of the overflow pipe.

In addition, the health and stability of the tree depends on its root system. The more soil resources the root system explores, the better the tree will cope with heavy winds or rain loads and drought. Drainage of the system should be managed to attain optimum tree growth. Optimum water withdrawal from the reservoir was achieved in our experiments by the largest trees.

Depending on the site, soils may be very heterogenous, which may lead to an overall high infiltration rate. Therefore, even if infiltration rate samples indicate a low infiltration rate, there can be cracks in the soil which can lead water into the soil at a rapid pace. Depending on the area of the reservoir, there may be more or fewer cracks to increase the infiltration rate of the entire area. To determine this, it would be optimal to test the infiltration behavior of the entire area which would be used as structural soil reservoir before drawing conclusions from sampling. This may not be practical, however, and maximum water levels will need to be ensured by including drainage at the desired level. Our experiments showed that tree roots can grow into the subsoil and that this increases the infiltration rate. The increase in infiltration rate in our experiments was considerable, a 63% increase overall. For example, disregarding the pine bark and the tree roots, the cylinder had a volume of approximately 5.5 L (1.45 gal). Time of infiltration for 1 L (0.26 gal) of water could be 200 s. Calculated as a rate, this would have been 1.8 cm/min (0.7 in/min) for the cylinder with a 15.2 cm (5.98 in) diameter. This rate could be increased by root channels to 4.2 cm/min 1.65 in/min). The effect of root growth on drainage could be mitigated by a number off factors. First, if water remains in the bottom of the stormwater reservoir for long periods of time, roots will likely not exploit this soil region and therefore will not reach the compacted subsoils below. In addition, our experiments were conducted in containers. Roots were observed to exit the bottoms of the pots in many cases, presumably providing a tunnel from the pine bark reservoir all the way through to the outside air. In the field, roots will terminate within the soil layers and drainage may be impeded by dense layers below the portion of subsoil exploited by roots.

In summary, structural soils have a higher porosity than common, compacted, urban soils, which leads to higher infiltration, aeration, penetrable soil volume for tree roots, and stormwater detention. The high permeability of these substrates allows water to move freely through the system (both vertically and laterally). Soil heterogeneity and root growth into the soil can lead to higher infiltration rates than may be indicated through sampling.

Influence of drainage of the stormwater management reservoir on tree growth and development

As demonstrated by both experiments, different tree species have different rooting habits. Below the soil surface, the distribution and the area of absorptive surface of the root system affect the capability of the tree to extract soil water. The size of the root system of the particular tree depends on its requirements and tolerances. Factors such as water and nutrient availability, soil pH, penetrable soil volume, competition, and other environmental conditions play important roles. As mentioned earlier, trees in submerged soils may have a shallower root system, which can affect tree heath and stability. Normally, root system size is genetically determined and reflects evolutionary selection to give that species fitness for various environments. The root system that develops in a saturated stormwater reservoir may be large for a tree that tolerates wet conditions, and very small for one that does not. This can influence tree health immensely. For this reason, we selected bottomland species for this study as they would be expected to be the most likely candidates to perform well in this type of system.

In addition, depending on the geographical area, there may be periods of the year with very low precipitation. A tree may be able to cope with drought better when it has a deep root system because it may be able to reach deeper soil layers and may still have access to soil water. On the other hand, a tree with shallow, wide-ranging root system may be able to use water from light rains which do not reach deep soil layers. We would expect trees that tolerate wet soils and high pH, such as the two species in our experiment, to perform best in our proposed system. Many bottomland species are found in wet areas because they tolerate those conditions better than other species, or because standing water protects them from fire.

Many of these trees perform well in drier conditions and constitute a large proportion of our most common and successful street tree species. Tree species, such as *Taxodium distichum*, can grow in upland and bottomland soils, therefore submerged or drier soils. Among others, *Acer rubrum*, *Fraxinus nigra*, and *Ulmus americana* may also be good tree species for our proposed system.

Species selection is always an important factor when planting a tree at any site. Factors such as soil pH, water content/drainage, exposure to wind and radiation, space (below and above ground), and surrounding vegetation and buildings at the site will greatly influence the survival and development of the tree. It is necessary to evaluate each individual site to decide which tree is suitable and which is not. For a stormwater management facility utilizing structural soil and trees, it is important to know the soil conditions and infiltration behavior in addition to precipitation data for that particular area. This will help ensure that the design of the structural soil facility is suitable for the tree species selected and vice versa. As in all urban plantings, species selection is critical to long-term success. As described earlier, there are species such as *Fraxinus pennsylvanica* that may prefer well drained soils, but grow well in wet soils, (Burns and Honkala, 1990). Those species may be most suitable for areas with occasional heavy rains. Drought tolerance may be more critical in warmer climates.
In addition, different kinds of structural soil may influence the pH. CU® Structural Soil uses limestone in our area (Blacksburg, VA) and can have pH values of 7 or even 8, depending on the pH of the precipitation. The pH of Stalite was generally lower in our study, less than 7. Many trees do not tolerate high pH values. *Fraxinus pennsylvanica*, for example, tolerates pH values of 7.5 to 8 whereas the optimal soil pH for *Q. phellos* L is 4.5 to 5.5 (Burns and Honkala, 1990). Therefore, although *Q. phellos* is a common street tree and tolerates poor drainage, it would likely not thrive in this system.

Overall, a tree for a certain site should be suitable for the given space and environmental conditions such as temperature, radiation, wind exposure, space, below and above ground, soil pH, and water availability. The requirements are no different for a structural soil reservoir. Trees have to be suitable for the given conditions. For our proposed system, species would be suitable that are tolerant to high pH, flooding and drought, fast establishment would be desirable, and salt sensitive species should be avoided. There is a greater potential for trees to grow large in a structural soil reservoir than in mineral urban soils because of the higher porosity and thus higher penetrable volume of structural soil. For the same reason, the tree may be exposed to higher or lower soil water content, and higher pH in structural soil.

Potential for water uptake by trees from the structural soil reservoir

Tree water uptake is highly dependent on its root system and canopy area. Even though an individual tree may have a high transpiration rate, total leaf area and therefore total transpiration may be small. On the other hand, a tree with a low transpiration rate may take up more total water because of a greater leaf area. In our study, this phenomenon was observed for *Q. bicolor* trees. These trees had the highest transpiration rate in the slowly draining systems where the soils were submerged for much of the time. However, the daily total volume of was highest for trees in the moderate infiltration treatment because these trees had a greater overall leaf area. Keeping the tree healthy will increase the leaf area and is therefore critical to maximizing the total transpiration of that tree. Depending on the size of the soil water reservoir and number and sizes of the trees, transpiration can increase the capacity of the system. A drawback may be leaf drop during the fall. If the tree has a greater leaf area, there will be more leaves on the ground, which may need to be collected to avoid clogging of the system. If the site is paved with impervious surface, there must be ways for the water to reach the reservoir below the pavement from the side, perhaps through drains and pipes. If leaves restrict the flow, stormwater will not be collected and runoff will be increased. If a pervious pavement is used, care needs to be taken to prevent leaf litter from clogging the pavement pores.

If the tree has a large, widely distributed root system, especially if it also extends into the subsoil, the tree can benefit from the water resources in this larger soil volume. Larger trees also result in more overall water removed from the reservoir via transpiration. We found that trees can be capable of growing roots into compacted subsoil. Whether this will commonly occur in an actual stormwater reservoir needs to be investigated. We observed a rather shallow root system in the containers with slow infiltration rate. Therefore, we would not expect roots to grow into the subsoil below the structural soil reservoir if there is a constant water table within the system. In these conditions, where an increase of the infiltration rate through root growth would be most desirable, the root system may be very shallow instead. A large root system generally offers higher stability to withstand heavy winds or storms. In summary, optimizing tree size and health may also be the most beneficial for water removal from a stormwater reservoir.

Structural Soil

In our experiment we used CU® Structural Soil and a Stalite mix to explore how they might affect the functioning of the stormwater system. It seemed that the CU® Structural Soil was very stable, once compacted. This may partly be influenced by the weight and the angular shape of the lime stone. The Stalite consists of light-weight aggregates that are rather round in shape. The Stalite mix appeared to be less stable because the aggregate did not interlock well. It was possible to pull trees out of the Stalite without great effort, whereas it was not possible for trees in the CU® Structural Soil. Since our experiment was a container experiment, we did not use any kind of pavement. The mix may have very stable structure when covered with pavement which would keep it in place. Field experiments determining the stability of trees in such system utilizing Stalite or a comparable substrate would be of great interest to ensure that tree failure is not a concern.

Other differences between Stalite and CU® Structural Soil may be the porosity of the single aggregate. The CU® Structural Soil uses limestone whose single rocks are not porous. The Stalite is a heat expanded slate, similar to lava, which has a higher porosity. This may influence water relations of the substrate. Further experiments could include the determination of drought tolerance of trees grown in the Stalite-mix compared to those in CU® Structural Soil.

Overall, structural soil can be a suitable way to treat stormwater. Even if trees do not take up a significant amount of water to increase the capacity of the system, they will intercept a great amount of water, which by itself will decrease run off. A large tree in leaf can intercept 80% of the precipitation compared to a small tree, which may only intercept 16%. In addition to the greater leaf area of large trees, they have a more wide-ranging canopy (Xiao and McPherson, 2003). Leaf area and canopy size determine the amount of rainfall interception. Therefore, large trees have the potential to decrease runoff because less water reaches the ground. In addition, they also provide us with benefits that pay off, either economically by saving energy costs through shading and wind protection, ecologically, by decreasing air pollution, providing wildlife habitats, or just by increasing human well being.

References

Americast. 2004. Filterra® Stormwater Bioretention Filtration System. www.filterra.com (date of access 11-10-2006).

Andrade, A.D., F. Ramos, A.S. De, M. Loureiro, and R. Bastos. 1999. Flooding effects in seedlings of *Cytharesyllum myrianthum* Cham. and *Genipa americana* J.: responses of two neotropical lowland tree species. Rev. Bras. Bot. 22.

Ansley, R.J., W.A. Dugas, M.L. Heuer, and B.A. Trevino. 1994. Stem flow and porometer measurements of transpiration from honey mesquite *Prosopis glandulosa*. Journal of Experimental Botany. 45: 847-856.

ASTM. 2003. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3) 600 kN-m/m^3)), D698-00a. ASTM International.

Barley, K. 1963. Influence of soil strength on growth of roots. Soil Science. 96: 175-180.

Bassuk, N., J. Grabosky, and P. Trowbridge. 2005. Using Structural Soil™ in the Urban Environment. Urban Horticulture Institute. Cornell University. Ithaca, NY.

Bassuk, N., J. Grabosky, P. Trowbridge, and J. Urban. 1998. Structural Soil: An innovative medium under pavement that improves street tree vigor. American Society of Landscape Architects Annual Meeting (ASLA), 1998. www.hort.cornell.edu/uhi/outreach/csc/article.html.

Black, K.E., C.G. Harbron, M. Franklin, D. Atkinson, and J.E. Hooker. 1998. Differences in root longevity of some tree species. Tree Physiology. 18: 259-264.

Brady, N. and R. Weil. 1999. The Nature and Properties of Soils. Prentice Hall, Upper Saddle River, NJ.

Bramley, H., J. Hutson, and S. Tyerman. 2003. Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species *Eucalyptus largiflorens*. Plant and Soil. 253: 275-286.

Burns, R. and B. Honkala. 1990. Silvics of North America, Vol. 2 Hardwoods. U.S.D.A. Forest Service, Washington, DC.

Burton, G.J. and R. Pitt. 2002. Stormwater Effects Handbook: A toolbox for Watershed Managers, Scientists, and Engineers. CRC Press LLC, Boca Raton, FL, USA.

CBP. 2004. Urban Storm Water, Water Quality, Chesapeake Bay Program. www.chesapeakebay.net/info/stormwater.cfm (date of access 2-18-2006).

Celestian, S. and C. Martin. 2004. Rhizosphere, Surface, and Air Temperature Patterns at Parking Lots in Phoenix, Arizona, U.S. Journal of Arboriculture. 30: 245-252.

Cermák, J., J. Hruska, M. Martinovkaka, and A. Prax. 2000. Urban tree root systems and their survival near houses analyzed using ground penetrating radar and sap flow techniques. Plant and Soil. 219: 103-116.

CIA. 2005. The World Factbook: World. Central Intelligence Agency. USA. www.cia.gov/cia/publications/factbook/geos/xx.html (date of access 11-13-2006).

Clark, L.J., W.R. Whalley, and P.B. Barraclough. 2003. How do roots penetrate strong soil? Plant and Soil. 255: 93-104.

Cohen, B. 2004. Urban growth in developing countries: A review of current trends and a caution regarding existing forecasts. World Development. 32: 23-51.

Costello, L. and K. Jones. 2003. Reducing Infrastructure: Damage By Tree Roots: A Compendium of Strategies. Western Chapter, International Society of Arboriculture.

Craul, P. 1992. Urban Soil in landscape design. John Wiley & Sons, Inc., New York.

CWP. 2003. The Compaction of Urban Soils. Watershed Protection Techniques. 3: 661-665.

Daddow, R. and G. Warrington. 1983. Growth-limiting soil bulk densities as influenced by soil texture. WSDG Report (WSDG-TN-00005). Jan. 1983. Watershed Systems Development Group. U.S.D.A. Forest Service. Fort Collins, CO.

Day, S. and N. Bassuk. 1994. A review of the effects of soil compaction and amelioration treatments on landscape trees. Journal of Arboriculture. 20: 9-17.

Day, S.D., J.R. Seiler, and N. Persaud. 2000. A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at differing soil water contents. Tree Physiology. 20: 257-263.

Dennison, M. 1996a. Stormwater Discharges: Regulatory Compliance and Best Management Practices. CRC Press, Inc., Boca Raton, FL, USA.

Dennison, M.S. 1996b. Storm Water Discharges: Regulatory Compliance and Best Management Practices. Lewis Publishers, Boca Raton, FL.

EPA. 1993. Guidance Specifying Management Measures for Sources of Nonpoint Pollution of Coastal Waters. U.S. Environmental Protection Agency.

EPA. 1999. Preliminary Data Summary of Urban Stormwater Best Management Practices: Chapter 4: Environmental Assessment. U.S. Environmental Protection Agency.

EPA. 2000. Naphthalene: Hazard Summary. U.S. Environmental Protection Agency. www.epa.gov/ttn/atw/hlthef/naphthal.html (date of access 11-21-2006).

EPA. 2002a. Federal Water Pollution Control Act. U.S. Environmental Protection Agency.

EPA. 2002b. Water Quality Assessment Part I: Rivers and Streams, 2000 National Water Quality Inventory, U.S. Environmental Protection Agency.

EPA. 2002c. Water Quality Conditions in the United States: A Profile from the 2000 National Water Quality Inventory, U.S. Environmental Protection Agency.

EPA. 2004a. Managing Urban Runoff. Polluted Runoff (Nonpoint Source Pollution). U.S. Environmental Protection Agency.

EPA. 2004b. National Pollutant Discharge Elimination System (NPDES)-Phases of the NPDES Stormwater Programm. U.S. Environmental Protection Agency. http://cfpub.epa.gov/npdes/stormwater/swphases.cfm (date of access 2-15-2006).

EPA. 2004c. Nonpoint Source Pollution: The Nation's Largest Water Quality Problem. Polluted Runoff (Nonpoint Source Pollution). U.S. Environmental Protection Agency.

EPA. 2006. Pyrene. CAS Number 129-00-0. U.S. Environmental Protection Agency. www.epa.gov/epaoswer/hazwaste/minimize/factshts/pyrene.pdf (date of access 11-12-2006).

Evans, M., N. Bassuk, and P. Trowbridge. 1990. Sidewalk Design for Tree Survival + Strategies for Healthy Root-Systems in Urban Plantings. Landscape Architecture. 80: 102-103.

EXTOXNET. 1994. Pesticide Information Profile: Copper Sulfate. pmep.cce.cornell.edu/profiles/extoxnet/carbaryl-dicrotophos/copper-sulfate-ext.html (date of access 11-19-2006).

Exum, L. 2005. Estimating and Projecting Impervious Cover. U.S. Environmental Protection Agency Science Forum: Collaborative Science for Environmental Solutions.

Foster, R.S. and J. Blaine. 1978. Urban tree survival: trees in the sidewalk. Journal of Arboriculture. 4: 14-17.

Frederick, R., R. Goo, and M. Keefe. 2003. EPA's Management Measures Guidance to control Nonpoint Source Pollution from Urban Areas. National Conference on Urban Strom Water: Enhancing Programs at the Local Level.

Grabosky, J. and N. Bassuk. 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. Journal of Arboriculture. 21: 187-200.

Grabosky, J. and N. Bassuk. 1996. Testing of structural urban tree soil materials for the use under pavement to increase street tree rooting volumes. Journal of Arboriculture. 22: 255-263.

Grabosky, J., N. Bassuk, L. Irwing, and H.v. Es. 1998. Pilot Field Study of structural soil materials in pavement profiles. The Landscape Below Ground II: Proceedings of an International Workshop on Tree Root Development in Urban Soils. (San Francisco, CA: International Society of Arboriculture), 210-221.

Grabosky, J., N. Bassuk, L. Knutson, and G. Yoko. 2004. Growing Trees in a Cement Forest. Land Development Today: 43-44.

Grabosky, J., N. Bassuk, and B. Marranca. 2002. Preliminary findings from measuring street tree shoot growth in two skeletal soil installations compared to tree lawn plantings. Journal of Arboriculture. 28: 106-108.

Grabosky, J., N. Bassuk, and P. Trowbridge. 1999. Structural Soils: A new medium to allow urban trees to grow in pavement. Landscape Architecture Technical Information Series (LATIS).

Grabosky, J. and E. Gilman. 2004. Measurement and prediction of tree growth reduction from tree planting space design in established parking lots. Journal of Arboriculture. 30: 154-164.

Graves, W. 1998. Consequences of high soil temperatures in The Landscape below ground II:Proceedings of an International Workshop on Tree Root Development in Urban Soils. International Society of Arboriculture.

Harris, R., J. Clark, and N. Matheny. 2004. Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines. Prentice Hall, Upper Saddle River, NJ.

Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soil. Forest Science. 27: 660-666.

Hightshoe, G. 1988. Native Trees, Shrubs, and Vines for Urban and Rural America. Van Nostrand Reinhold, New York, NY.

Horner, R., J. Skupien, E. Livingston and H. Shaver. 1994. Fundamentals of urban runoff management: technical and institutional issues. Prepared by the Terrene Institute, Washington, DC, in cooperation with the U.S. Environmental Protection Agency.

Kadlec, R. and R. Knight. 1996. Treatment Wetlands. CRC Press, Inc., Boca Raton, FL, USA.

Kalter, B. no date-a. Conventional Tree Pits are designed for failure, CU Soil, Amereq, Inc., New City, NY.

Kalter, B. no date-b. A new system to integrate trees and pavement, CU Soil, Amereq, Inc., New City, NY.

Konijnendijk, C., K. Nilsson, T. Randrup, and J. Schipperijn. 2005. Urban Forests and Trees. Springer-Verlag, Berlin, Heidelberg, Germany.

Kozlowski, T. 1943. Transpiration rates of some forest tree species during the dormant season. Plant Physiology. 18: 252-260.

Kozlowski, T. and S. Pallardy. 1997. Physiology of Woody Plants. Academic Press, San Diego, CA.

Kramer, P. and T. Kozlowski. 1960. Physiology of Trees. McGraw-Hill, New York, NY.

Krizek, D. and S. Dubik. 1987. Influence of Water Stress and restricted root volume on growth and development of urban trees. Journal of Arboriculture. 13: 47-55.

Kuo, F. and W. Sullivan. 2001. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? Environment and Behavior. 33: 343-367.

Larcher, W. 1975. Physiological Plant Ecology. Springer-Verlag, Berlin, Germany.

Lindsey, P. and N. Bassuk. 1991. Specifying soil volume to meet the water needs of mature urban street trees and trees in containers. Journal of Arboriculture. 17: 141-149.

Lipiec, J. and I. Hakansson. 2000. Influences of degree of compactness and matric water tension on some important plant growth factors. Soil & Tillage Research. 53: 87-94.

Lowerts, G.A. and J.M. Stone. 1982. The effect of soil bulk density on nursery sweetgum seedling growth. Tree Planters' Notes. 33: 3-5.

Marshall, J.D. no date. How trees grow quickly. Forest Resources. College of Natural Resources. University of Idaho. www.cnr.uidaho.edu/forres/Powerpoint/Marshall%20-%20How%20trees.ppt (date of access 11-02-2006).

Materechera, S.A., A.R. Dexter, and A.M. Alston. 1991. Penetration of very strong soils by seedling roots of different plant species. Plant and Soil. 135: 31-34.

Mengel, K. and E. Kirkby. 2001. Principles of Plant Nutrition. Kluwer Academic Publishers, Netherlands.

Metropolitan Council. 2003. Minnesota Urban Sites BMP Manual: Stormwater Wetlands. Metropolitan Council.

Montague, T. and R. Kjelgren. 2004. Energy balance of six common landscape surfaces and the influence of surface properties on gas exchange of four containerized tree species. Scientia Horticulturae. 100: 229-249.

Nesmith, D.S., D.C. Bridges, and J.C. Barbour. 1992. Bell Pepper Responses to Root Restriction. Journal of Plant Nutrition. 15: 2763-2776.

Nowak, D.J. 1993. Atmospheric carbon reduction by urban trees. Journal of Environmental Management. 37: 207-217.

NRCS. 2000a. Land Converted to Development, U.S.D.A. Natural Resources Conservation Service. www.nrcs.usda.gov/technical/land/meta/m5847.html (date of access 1-25-2006).

NRCS. 2000b. Land uses converted to developed land, 1982-1997, U.S.D.A. Natural Resources Conservation Service. www.nrcs.usda.gov/technical/land/mappdfs/m5907.pdf (date of access 1-25-2006).

NRCS. 2003. National Resources Inventory, U.S.D.A. National Resources Conservation Service. www.nrcs.usda.gov/TECHNICAL/land/nri03/nri03landuse-mrb.html (date of access 1-25-2006).

NRCS. no date. United States Annual Precipitation. U.S.D.A. Natural Recources Conservation Service. www.ncgc.nrcs.usda.gov/products/datasets/images/climate/maps/usa.jpg (date of access 1-25-2006).

NWS. 2006. Precipitation Frequency Data Server, NOAA's National Weather Service, Hydrometeorological Design Studies Center.

Pitt, R., S. Clark, and K. Parmer. 1994. Potential groundwater contamination from intentional and nonintentional stormwater infiltration. U.S. Environmental Protection Agency.

Pitt, R., R. Field, M. Lalor, and M. Brown. 1995. Urban Stormwater Toxic Pollutants - Assessment, Sources, and Treatability. Water Environment Research. 67: 260-275.

Quigley, M. and T. Lawrence. 2002. Multifunctional Landscaping: Putting your parking lot design requirements to work for water quality. University of Illinois Extension. www.urbanext.uiuc.edu/lcr/LGIEN2002-0017.html (date of access 3-17-2006).

Randolph, J. 2004a. Land Use, Stream Flow, and Runoff Pollution in Environmental Land Use Planning and Management. Island Press, Washington, DC.

Randolph, J. 2004b. Looking Back, Looking Forward: The Evolving Nature of Environmental Planning. Association of Collegiate Schools of Planning (ACSP), Portland, OR.

Randolph, J. 2004c. Storm Water Management and Stream Restoration in Environmental Land Use Planning and Management. Island Press, Washington, DC.

Russell, R. 1977. Plant root system, Their functions and interactions with the soil. McGraw-Hill Company (UK) limited. London; New York.

Salwasser, H. and E. McPherson. 1999. Perspectives on research and development needs in urban and community forestry. Pacific Southwest Research Station. Albany, CA. U.S.D.A. Forest Service.

Schueler, T., P. Kumble, and M. Heraty. 1992 A Current Assessment of Urban Best Management Practices: Techniques for Reducing Non-Point Source Pollution in the Coastal Zone. Department of Environmental Programs, Metropolitan Washington Council of Governments, Washington, DC.

Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington Metropolitan Water Recourses Planning Board.

Smiley, T. 2005. Root growth near vertical root barriers. Journal of Arboriculture. 31(3): 150-152.

SMRC. 2004. Stormwater Management Fact Sheet. Stormwater Manager's Resource Center. Center for Watershed Protection. U.S. Environmental Protection Agency. www.stormwatercenter.net (date of access 1-25-2006).

SMRC. no date. Recharge Sizing, Stormwater Manager's Resource Center. U.S. Environmental Protection Agency. http://www.stormwatercenter.net/Manual_Builder/Sizing_Criteria/Recharge/Recharge%20Volume%20Requirements.htm (date of access 1-25-2006).

Sokal, R. and F. Rohlf. 1995. Biometry. 3rd Edition. W.H. Freeman and Company. New York, NY, USA.

Steinberg, S., C.H.M. Vanbavel, and M.J. Mcfarland. 1989. A Gauge to Measure Mass-Flow Rate of Sap in Stems and Trunks of Woody-Plants. Journal of the American Society for Horticultural Science. 114: 466-472.

Szabo, A., A. Osztoics, and F. Szilagyi. 2001. Natural wastewater treatment in Hungary. Water Science Technology. 44: 331-338.

Thomas, P. 2000. Trees: Their Natural History. Cambridge University Press, Cambridge, United Kingdom.

Tyrvainen, L. 1999. Monetary valuation of urban forest amenities in Finland, Vantaa. Academic dissertation. Finish Forest Research Institute. Vantaa.

USPTO. 1998. Urban tree soil to safely increase rooting volumes. United States Patent 5,849,069. United States Patent and Trademark Office.

Vortechnics Inc. 2005. Total Stormwater Solutions, CD ROM. www.vortechnics.com.

Whalley, W.R., P.B. Leeds-Harrison, P.K. Leech, B. Riseley, and N.R.A. Bird. 2004. The hydraulic properties of soil at root-soil interface. Soil Science. 169: 90-99.

Winter, R. 2000. National Pollutatnt Removal Performance Database for Stormwater Treatment Practices. Office of Science and Technology. U.S. Environmental Protection Agency in association with TetraTech, Inc.

Wolf, K.L. 2003. Public response to the urban forest in inner-city business districts. Journal of Arboriculture. 29: 177-126.

Xiao, Q. and E. McPherson. 2003. Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosystems. 6: 291-302.

Zwack, J.A., W.R. Graves, and A.M. Townsend. 1999. Variation among red and Freeman maples in response to drought and flooding. Hortscience. 34: 664-668.

Appendix I

Specifications for Structural Soils

Installation Guidelines – Stalite Structural Soil Mix for Trees

PART 1 – GENERAL

PART 2 - PRODUCTS

2.1 MATERIALS

A. STRUCTURAL SOIL MIX

1. The Structural Soil Mix shall be Stalite Structural Soil Mix (a special pre-mixed blend of 80% 3/4" graded **"STALITE"** Expanded Argillitic Slate Aggregate and 20% approved sandy clay loam).

B. TREE PIT BACKFILL PLANTING MIX

1. The tree pit backfill planting mix shall be high quality topsoil mixed 50% with of the excavated structural soil.

PART 3 - EXECUTION

3.1 PREPARATION

A. GENERAL

1. The paving contractor shall obtain necessary approvals before placing each SSM layer.

2. The paving contractor shall use adequate numbers of skilled workmen who are thoroughly trained in the necessary crafts and are completely familiar with the specified requirements and methods needed for proper performance of the work in this section.

3. The contractor must provide access for and cooperate with the testing laboratory.

4. Adequacy of the final compaction of all elements requiring compaction shall be determined in the field by the engineer to achieve the minimum specified compaction level.

B. PREPARING SUBGRADE

1. The subgrade shall be prepared according to the following procedure:
   a. Remove all organic matter, debris, loose material and large rocks.
   b. Dig out soft and mucky spots and replace with suitable material.
   c. Loosen hard spots and uniformly compact the subgrade to 95% of its maximum dry density.

C. PERFORATED UNDERDRAIN SYSTEM

1. The underdrain system shall be Installed, including sock or soil separator fabric, according to drawing and specifications, and connected to the storm drain.

3.2 PLACING STRUCTURAL SOIL MIX BY PAVING CONTRACTOR

A. GENERAL

1. Adequacy of the final compaction shall be determined in the field by the engineer by proof roll.

2. The soil vents and drains shall be installed as specified and structural soil compacted under and around each pipe.

3. **Optional – If wooden tree pit forms are used, they shall be installed as directed by the Landscape Architect.**

4 The SSM shall be placed in approximately uniform lifts over the entire area of project and each lift compacted, including the open tree pit areas. Construction equipment, other than for compaction, shall not operate on the exposed structural soil mix. Over-compaction should be avoided. No foot or equipment traffic should be allowed on the compacted material until the paving is placed.

5. The drip irrigation system is to be installed and tested during the screenings laying course installation to avoid disturbing the compaction of the mix.

B. COMPACTING

1. Use of portable vibratory plate compacting machine (Recommended)

a. Place structural soil mix in horizontal lifts not exceeding 12 inches of compacted depth. Use a minimum of two passes, of not less than 10 seconds per pass, before moving the vibratory plate to the next adjacent location. Additional passes may be required and should be determined in the field by the engineer to insure stability of the layer. Continue placing and compacting 12” lifts until the specified depth is reached.

2. Use of vibratory steel roller (for large areas)

a. For large spaces, a vibratory steel roller weighing no more than 12 tons static weight can be used. Horizontal lifts should not exceed 12” compacted. The minimum number of passes is two and maximum number is four. Additional passes may be required and should be determined in the field by the engineer to insure stability of the layer.

3.3 PLACING SCREENINGS FOR LAYING COURSE BY PAVING CONTRACTOR

A. GENERAL

1. All necessary approvals shall be obtained from the contractor before placing the sand..

B. PLACING LAYING COURSE BY THE PAVING CONTRACTOR

1.The coarse sand for the laying course shall be placed by using these procedures:

a. Spread the sand/screenings evenly over the area to be paved and at least 6 inches from the
end of the area.

b. Compact the sand laying course using vibrating plate compacting equipment until no densification is achieved with additional passes by the vibrating equipment.

c. Screed and level a final seating layer over the compacted layer of the laying course to achieve the thickness and grades specified on the drawings after final compaction.

d. Do not disturb the laying course once it is compacted, screeded and leveled. If the laying course is disturbed, re-compact and reshape it until it meets the requirements in this section.

3.4 PAVER INSTALLATION

A. Stub out air vents as specified on drawings.

B. Install the pavers as per drawings and specifications.

C. No vehicles or heavy equipment are permitted on the compacted layer course until pavers are completely installed.

3.5 CONCRETE PLACEMENT

A. Concrete can be placed as specified directly on the compacted structural soil.

B. Asphalt paving requires a 4” layer of ABC stone to support the equipment to prevent horizontal displacement and rutting of the structural soil.

PART 4 - TREE PLANTING

4.1 TREE PIT PREPARATION BY LANDSCAPE CONTRACTOR

A. TREE PIT EXCAVATION

1. The Landscape Contractor shall excavate the tree pit using these procedures:

a. Excavate the structural soil mix to a depth equal to the height of the root ball of the tree to be planted. Remove the SSM to within a one feet of the edge of the paved area.

b. Place the tree in the pit and backfill as soon as possible, as recommended in section “B”. Remove any excess soil on the top of the root ball that was filled above the root collar by the nursery. No tree pit shall remain excavated for more than 2 hours unless forms are used.

B. TREE PIT BACKFILL PLANTING MIX

1. The landscape contractor shall backfill the tree pit by using these procedures:

a. Remove any optional wooden forms. Immediately place the tree in the pit as detailed and mix the excavated structural soil 50:50 with the specified topsoil. Backfill the planting mix into the pit around the root ball in one foot lifts and tamp until firm.

b. Tamp the planting mix in one foot lifts until the pit is filled to the specified grade
above the planting.

c. Dispose of the excavated structural soil mix (do not re-use as structural soil).

d. Attach drip irrigation as specified.

CU® Structural Soil: Description and Specification/abridged

1.01 SAMPLES AND SUBMITTALS

A. At least 30 days prior to ordering materials, the Contractor shall submit to the Engineers representative samples, certificates, manufacturers literature and certified tests for materials specified below. No materials shall be ordered until the required samples, certificates, manufacturers literature and test results have been reviewed and approved by the Engineer. Delivered materials shall closely match the approved samples. Approval shall not constitute final acceptance. The Engineer reserves the right to reject, on or after delivery, any material that does not meet these specifications.

B. Submit two - one half cubic foot representative samples of Clay Loam and two - two cubic foot representative samples Structural Soil mixes in this section for testing, analysis and approval. Submit one set of samples for every 500 CY of material to be delivered. In the event of multiple source fields for Clay Loam, submit a minimum of one set of samples per source field or stockpile. Samples shall be taken randomly throughout the field or stockpile at locations as directed by the Engineer and packaged in the presence of the Engineer. Contractor shall deliver all samples to testing laboratories and shall have the test results sent directly to the Engineer. Samples shall be labeled to include the location of the source of the material, the date of the sample and the Contractors name. One of the two samples is to be used by the testing laboratory for testing purposes. The second sample of all Clay Loam and Structural Soil shall be submitted to the Engineer at the same time as test analysis as a record of the soil color and texture.

1. Submit the locations of all source fields for Clay Loam.
2. Submit a list of all chemicals and herbicides applied to the Clay Loam for the last five years and a list of all crops grown in the Clay Loam source fields for the last three years.

C. Submit soil test analysis reports for each sample of Clay Loam and Structural Soil from an approved soil-testing laboratory. The test results shall report the following:

1. The soil testing laboratory shall be approved by the Engineer. The testing laboratory for particle size and chemical analysis may be a public agricultural extension service agency or agricultural experiment station.

2. Submit a particle size analysis including the following gradient of mineral content:

USDA Designation Size in mm.

Gravel	+2mm
Sand	0.05 -2 mm
Silt	0.002-0.05 mm
Clay	minus 0.002 mm

Sieve analysis shall be performed and compared to USDA Soil Classification System.

D. Submit a chemical analysis, performed in accordance with current AOAC Standards, including the following:
   a. pH and Buffer pH.
   b. Percent organic matter as determined by the loss of ignition of oven dried samples.
   c Analysis for nutrient levels by parts per million including nitrate nitrogen, ammonium nitrogen, phosphorus, potassium, magnesium, manganese, iron, zinc, calcium and extractable aluminum. Nutrient test shall include the testing laboratory recommendations for supplemental additions to the soil as calculated by the amount of material to be added per volume of soil for the type of plants to be grown in the soil.
   d. Analysis for levels of toxic elements and compounds including arsenic, boron, cadmium, chromium, copper, lead mercury, molybdenum, nickel, zinc and PCB. Test results shall be cited in milligrams per kilogram.
   e. Soluble salt by electrical conductivity of a 1:2 soil/water sample measured in Milliohm per cm.
   f. Cation Exchange Capacity (CEC).

1. Submit 5-point minimum moisture density curve AASHTO T 99 test results for each Structural Soil sample without removing oversized aggregate.

2. Submit California Bearing Ratio test results for each Structural Soil sample compacted to peak standard density. The soaked CBR shall equal or exceed a value of 50.

3. Submit measured dry-weight percentage of stone in the mixture.

4. The approved Structural Soil samples shall be the standard for each lot of 500 cubic yards of material.

5. All testing and analysis shall be at the expense of the Contractor.

1.02 DELIVERY, STORAGE, AND HANDLING

A. Do not deliver or place soils in frozen, wet, or muddy conditions. Material shall be delivered at or near optimum compaction moisture content as determined by

AASHTO T 99 (ASTM D 698). Do not deliver or place materials in an excessively moist condition (beyond 2 percent above optimum compaction moisture content as determined by AASHTO T 99 (ASTM D 698).

B. Protect soils and mixes from absorbing excess water and from erosion at all times. Do not store materials unprotected from large rainfall events. Do not allow excess water to enter site prior to compaction. If water is introduced into the material after grading, allow material to drain or aerate to optimum compaction moisture content.

MATERIALS

2.01 CLAY LOAM

A. Clay Loam / Loam shall be a " loam to clay loam" based on the "USDA classification system" as determined by mechanical analysis (ASTM D-422) and it shall be of uniform composition, without admixture of subsoil. It shall be free of stones greater than one-half inch, lumps, plants and their roots, debris and other extraneous matter over one inch in diameter or excess of smaller pieces of the same materials as determined by the Engineer. It shall not contain toxic substances harmful to plant growth. It shall be obtained from areas which have never been stripped of top soil before and have a history of satisfactory vegetative growth. Clay Loam shall contain not less than 2% nor more than 5% organic matter as determined by the loss on ignition of oven-dried samples.

B. Mechanical analysis for a Loam / Clay Loam shall be as follows:

Textural Class	% of total weight
Gravel	less than 5%
Sand	20 - 45%
Silt	20 - 50%
Clay	20- 40%

C. Chemical analysis: Meet or be amended to meet the following criteria.

1. pH between 6.0 to 7.6
2. Percent organic matter 2 -5% by dry weight.
3. Nutrient levels as required by the testing laboratory recommendations for the type of plants to be grown in the soil.
4. Toxic elements and compounds below the United States Environmental Protection Agency Standards for Exceptional Quality sludge or local standard; whichever is more stringent.
5. Soluble salt less than 1.0 Millimho per cm.
6. Cation Exchange Capacity (CEC) greater than 10
7. Carbon/Nitrogen Ratio less than 33:1.

2.02 CRUSHED STONE

A. Crushed Stone shall be a DOT certified crushed stone. Granite and limestone have been successfully used in this application. Ninety-100 percent of the stone should pass the 1.5 inch sieve, 20-55 percent should pass the 1.0 inch sieve and 10 percent should pass the 0.75 inch sieve. A ratio of nominal maximum to nominal minimum particle size of 2 is required

B. Acceptable aggregate dimensions will not exceed 2.5:1.0 for any two dimensions chosen.

C. Minimum 90 percent with one fractured face, minimum 75 percent with two or more fractured faces.

D. Results of Aggregate Soundness Loss test shall not exceed 18 percent. Losses from LA Abrasion tests shall not exceed 40%.

2.03 HYDROGEL

A Hydrogel shall be a potassium propenoate-propenamide copolymer Hydrogel or equivalent such as that which is manufactured under the name Gelscape by Amereq Corporation. (800) 832-8788

2.04 WATER

A. The Contractor shall be responsible to furnish his own supply of water to the site at no extra cost. All work injured or damaged due to the lack of water, or the use of too much water, shall be the Contractor's responsibility to correct. Water shall be free from impurities injurious to vegetation.

2.05 STRUCTURAL SOIL

A. A uniformly blended mixture of Crushed Stone, Clay Loam and Hydrogel, mixed to the following proportion:

MATERIAL	UNIT OF WEIGHT
Crushed Stone	80 units dry weight
Loam (screened)	as determined by the test of the mix. (Approx. 20 units dry weight)
Hydrogel	0.03 units dry weight/100units stone
Total moisture	(AASHTO T-99 optimum moisture)

B. The initial mix design for testing shall be determined by adjusting the ratio between the Crushed Stone and the Clay loam. Adjust final mix dry weight mixing proportion to decrease soil in mixture if CBR test results fail to meet acceptance (CBR > 50).

CONSTRUCTION METHODS

3.01 SOIL MIXING AND QUALITY CONTROL TESTING

A. All Structural Soil mixing shall be performed at the Contractor’s yard using appropriate soil measuring, mixing and shredding equipment of sufficient capacity and capability to assure proper quality control and consistent mix ratios. No mixing of Structural Soil at the project site shall be permitted. Portable pugging may be used

1. Maintain adequate moisture content during the mixing process. Soils and mix components shall easily shred and break down without clumping. Soil clods shall easily break down into a fine crumbly texture. Soils shall not be overly wet or dry. The contractor shall measure and monitor the amount of soil moisture at the mixing site periodically during the mixing process.

2. A Mixing procedure for front-end loader shall be as follows:

a. On a flat asphalt or concrete paved surface, spread an 8 inch to 12 inch layer of crushed stone.
b. Spread evenly over the stone the specified amount of dry hydrogel. Water the hydrogel on the stone before adding the soil.
c. Spread over the hydrogel and crushed stone a proportional amount of clay loam according to the mix design.
d. Blend the entire amount by turning, using a front-end loader or other suitable equipment until a consistent blend is produced.
e. Add moisture gradually and evenly during the blending and turning operation as required to achieve the required moisture content. Delay applications of moisture for 10 minutes prior to successive applications. Once established, mixing should produce a material within 1% of the optimum moisture level for compaction.

3. A pugging operation mixing procedure may be as follows:

a. Feed a known weight of crushed stone into the mixing trough.
b. Add hydrogel as a slurry into trough and mix slurry and stone into a uniform blend.
c. Meter in soil in proper proportion of Clay loam soil
While stone-slurry mixture is in motion.
Add water to bring mixture to target moisture content after factoring in water from the slurry and the Clay-loam moisture.
e. Auger out to stock pile or transport vehicle (or into pit if using a portable pugging operation).

B. The Contractor shall mix sufficient material in advance of the time needed at the job site to allow adequate time for final quality control testing as required by the progress of the work. Structural Soil shall be stored in piles of approximately 500 cubic yards and each pile shall be numbered for identification and quality control purposes. Storage piles shall be protected from rain and erosion by covering with plastic sheeting.

C. During the mixing process, the Contractor shall take two - one cubic foot quality control samples per 500 cubic yards of production from the final Structural Soil. The samples shall be taken from random locations in the numbered stockpiles as required by paragraph 1.03.B of this specification. Each sample shall be tested for particle size analysis and chemical analysis as described in Paragraph 1.03. C.2 and 3 above. Submit the results directly to the Engineer for review and approval.

D. The quality control sample Clay Loam-Crushed Stone ratio's shall be no greater or less than 2% of the approved test sample as determined by splitting a known weight of oven dried material on a #4 sieve. In the event that the quality control samples vary significantly from the approved Structural Soil sample, as determined by the Engineer, remix and retest any lot of soil that fails to meet the correct analysis making adjustments to the mixing ratios and procedures to achieve the approved consistency.

3.02 INSTALLATION OF STRUCTURAL SOIL MATERIAL

A. Install Structural Soil in 8 inch lifts and compact each lift. (Minimum of 24" total structural soil depth, preferably 36" recommended).

B. Compact all materials to peak dry density from a standard AASHTO compaction curve (AASHTO T 99). No compaction shall occur when moisture content exceeds maximum as listed herein. Delay compaction 24 hours if moisture content exceeds maximum allowable and protect Structural Soil during delays in compaction with plastic or plywood as directed by the Engineer.

C. Bring Structural Soils to finished grades as shown on the Drawings. Immediately protect the Structural Soil material from contamination by toxic materials, trash, debris, water containing cement, clay, silt or materials that will alter the particle size distribution of the mix with plastic or plywood as directed by the Engineer.

D. The Engineer may periodically check the material being delivered and installed at the site for color and texture consistency with the approved sample provided by the Contractor as part of the submittal for Structural Soil. In the event that the installed material varies significantly from the approved sample, the Engineer may request that the Contractor test the installed Structural Soil. Any soil which varies significantly from the approved testing results, as determined by the Engineer, shall be removed and new Structural Soil installed that meets these specifications.