STALITE ENVIRONMENTAL

A DIVISON OF CAROLINA STALITE COMPANY

Alternative Granular Media for Stormwater Bioretention and Filtration Applications

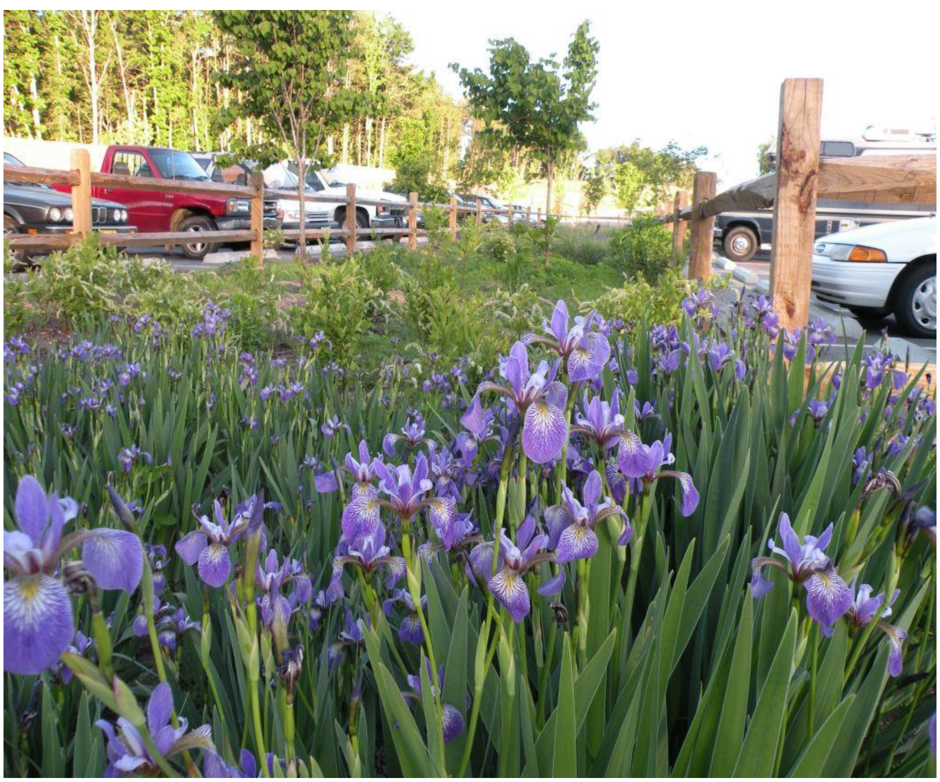


Figure 1 Richmond Hill Parking lot bioretention cell - Asheville NC

Alternative Granular Media for Stormwater Bioretention and Filtration Applications

Lightweight Expanded Slate Sand Media for Bioretention / Bio-infiltration Applications

ABSTRACT: Stalite expanded slate granular media is a clean, locally-available alternative for water treatment applications including rain gardens and sand filters. Stalite granular media possesses high nutrient holding capacity, hydraulic conductivity, and water retention capacity for longer service and a reduction in maintenance needs. Research and performance has provided a platform for Stalite to develop this document for use as a supplement to the user's local stormwater management requirements. Bioretention performance relies on several factors including the substrate media. Stalite granular media provides one more option.

Contents

Disclaimer

This work does not represent the official policy of the North Carolina Department of Natural Resources, North Carolina State University, or the University of North Carolina Charlotte .

This supplement includes reports of performance characteristics of Stalite Expanded Slate based on data and information from peer reviewed assessment test methods. Use of this information by the public or private sector is beyond Carolina Stalite's influence or control. The purpose of this supplement is to provide a tool that presents the performance of Stalite during consistent protocols of measurement. This supplement is not an endorsement of one BMP design over another and should not be interpreted as a recommendation by the institutions that contributed data.

Frequently Used Terms and Abbreviations

Abbreviation	Descriptor
ASTM	American Society for Testing & Materials
BET	Brunauer-Emmett-Teller an adsorption technique for calculating effective surface area
BMP	Best Management Practice as it relates to stormwater control
CEC	Cation Exchange Capacity
DWQ	Division of Water Quality ; A Division of NCDENR
FM	Fineness Module: percentage of aggregate fines < sieve #100
ID	Inside Diameter: as for a column
IWS	Internal Water Storage
mmhos	Milli-mhos: A mho is a reciprocal of an Ohm.
MS16	The gradation of expanded slate ceramic fines that fall within the USGS parameters for sand according to size (symbol for smaller than or equal to 0.2mm), hardness via Mohs Hardness Scale, and chemical composition. A manufactured sand graded from the screenings of crushed expanded slate
NCDACS	North Carolina Department of Agriculture & Consumer Services
NCDENR	North Carolina Department of Environment & Natural Resources
NCSU BAE	North Carolina State University – Biological & Agricultural Engineering; A department in both the College of Engineering and the College of Agriculture & Life Sciences
OM	Organic Matter
SLA	Structural Lightweight Aggregate
TCLP	Toxicity Characteristic Leaching Procedure
TSS	Total Suspended Solids
USDA	United States Department of Agriculture
USGS	United States Geological Survey

Term	Definition
Meta-Argillite	A fine-grained sedimentary rock composed predominantly of indurated clay particle that has been through metamorphism.

Sand	A loose aggregate of unlithified mineral or rock particles of sand size $^{1}/_{16}$ mm to 2 mm; an unconsolidated deposit consisting essentially of medium-grained clastic particles.
Trommel	A screened cylinder used to separate materials by size
Uwharrie Mountains	A mountain range in NC spanning the counties of Randolph, Montgomery, Stanly, and Davidson; The range's foothills stretch into Cabarrus, Anson, Union counties, and terminate in the hills of Person County

Stalite Expanded Slate

Figure 2 Stalite Lightweight Expanded Slate Coarse Aggregate

Stalite expanded slate is a processed structural lightweight aggregate (SLA) that is produced by firing a natural raw sedimentary meta-argillite that originated from volcanic activity. The raw slate is heated in rotary kilns to temperatures in excess of 2000 ° F. At this temperature, the gasses in the rock expand thus creating a light, porous, non-toxic, durable, granular ceramic. SLA's are used throughout the world in applications that include lightweight concrete and masonry units, chip seal and road surfacing, geotechnical and structural soils, horticulture and water treatment. The extraordinary raw slate deposit used to make Stalite is located in the foothills of the Uwharrie Mountains in North Carolina. The Carolina Stalite Company is the largest single lightweight aggregate production facility in the world. Family owned for over 60 years, it is the leading supplier of SLA in the eastern U.S.

Figure 3 Cape Fear Botanical Gardens –Fayetteville NC- Load Bearing, High Infiltration Stalite Media with Zoysia Turf Overlay.

Our Philosophy

Stalite Environmental is the Division for horticulture and water treatment products of the Carolina Stalite Company. Our philosophy is simple: mimic nature by providing the best media for establishing healthy plant roots and soil life for long-term ecological, environmental, and economic benefits. Our lightweight aggregate products can accomplish this in some of the harshest environments. Healthy, roots and root zones are our mission, whether the application is green roof, structural soils for trees and turf, or stormwater BMPs.

Figure 4 Bioretention Cell at the Alumni Field House - Elon University in Elon, NC (2012)

Stalite MS16, manufactured sand graded from the screenings of crushed expanded slate, enhances the natural physical and biological processes in vegetated bioretention by promoting healthy root systems that contribute to the remediation of pollutants found in stormwater runoff. This allows planners and developers a broader palette of BMP designs to meet the required nutrient load reductions, aesthetics, and maintenance costs. Engineers and planners dedicate hours to designing stormwater control systems. Therefore, the soils and filter media must be thoughtfully selected in order to fulfill the concept from the drawing board to the field. This supplement defines the properties of Stalite, presents test reports and case studies describing Stalite performance as it pertains to bioretention for hydraulic conductivity, water holding capacity, plant growth, and pollutant reduction.

Stalite Physical Properties

Figure 5 Stalite MS16 Production at the Carolina Stalite Company Gold Hill Plant.

Stalite's production methods eliminate waste by utilizing our post-manufactured, pre-consumer recycled screenings in a fraction designated as MS16. It is our alternative to standard quarry silica, granite, or quartz sand for bioretention root zones and filtration layers.

In the southeast, silica sand is the most popular component for bioretention soils. It provides slow infiltration rates for extended ponding time of stormwater runoff. Extended retention does contribute to treatment of nitrogen. Phosphorus removal is not abetted by extended retention. Silica sand particles are more sensitive to sediment accumulation, which slows infiltration and leaves the root zone layers in a saturated state that is not conducive for healthy plants.

MS16 particles settle into an open gapped substrate that resists clogging; especially during extreme rainfall events. The additional surface area and CEC improves treatment by adsorption and retention. Even when compacted in place, the angular expanded slate particles retain their porous surface areas. Stalite MS16 possesses the durability of typical gravel and sand but weighs 0.78 tons per cubic yard dry-loose. Stalite expanded slate is the strongest, most durable of SLA manufactured; it will not break down over time.

Figure 6 The Trommel and Belt Screening System at Stalite Plant - Gold Hill, NC

Figure 7 A sample of Stalite MS16 Expanded Slate.

STALITE ENVIRONMENTAL

Physical Characteristics

Physical Characteristic	English	Metric
Porosity (%)	49 %	
Bulk Density Dry	$61.5 \frac{lbs}{CF}$	$0.985 \frac{t}{m^3}$
Bulk Density SSD	$70 \frac{lbs}{CF}$	$1.122 \frac{t}{m^3}$
Absorption (%)	14 %	
Single Point Surface Area	$0.242 \frac{m^2}{g}$	
BET Surface Area	$0.2508 \frac{\mathrm{m}^2}{\mathrm{g}}$	

Table 1. Physical Properties Chart

MS16 Grain Size Distribution Chart		
Sieve Size #	mm	% Retained
4	4.75	0-3
8	2.36	0-10
16	1.18	34-54
30	0.60	59-72
50	0.30	75-83
100	0.15	84-92
200	0.075	90-92
Fine Material < #200	FM	88-92

Table 2. Stalite Gradation Chart

Infiltration Rate and Hydraulic Conductivity

Table 3 Saturated Hydraulic Conductivity (Ksat) of Stalite Porous Materials

	Sample	K_{sat} @ 20° C			
		cm/sec	cm/hr	in/min	in/hr
With 100% Compaction (ASTM D 5084)	Stalite MS16 Sand	0.00078	2.8	0.02	1.2
	MS16 80% + Pine Bark 20%	0.00060	2.16	0.015	0.9
Without Compaction (ASTM D 2434)	Stalite MS16 Sand	0.046	165.6	1.085	65.2
	MS16 80% + Pine Bark 20%	0.012	41.4	0.27	16.3

In properly designed bioretention cells, Stalite media allows stormwater runoff to drain into the soil within 12 hours and drain 24 inches below the soil surface within 48 hours depending on cell depth, in-situ soils, and under-drain configuration. The infiltration rate of loose-fill bioretention media containing 80% MS16 by volume averages 16 inches per hour, whereby primary filtration takes place, peak flow runoff is controlled, TSS is captured and vegetative root zones are re-aerated. Additional treatment continues by way of adsorption and retention.

Figure 8 Rhodes Stadium Parking Lot Bioretention Cell, Elon University – Elon, NC (2011)

MS16 media can be compacted in place to satisfy particular infiltration rules. There are different techniques used in the field that achieve different rates of compaction. In the case of bioretention cells using MS16 sand, walking along the surface of the sand will yield a compaction of 95-100%. MS16 media compacted to 100% can yield an infiltration rate of 1.02 inches per hour with that infiltration rate being relative to the amount of compaction forces applied to the sand. If Stalite MS16 is compacted to a rate of 95%, an infiltration rate within the range of 2-4 inches per hour can be achieved.

Different designs situations, particularly for urban retrofits, do benefit from the MS16 infiltration rates in devices that include deep storage zones such as what you would find in an Internal Water Storage (IWS) device. More specifically, IWS is a configuration within a bioretention cell whereby a 45° upturned PVC elbow creates a saturated layer at the bottom of the bioretention cell. The upturned elbow creates a sump effect on the water within the media preventing quick outflow. An IWS configuration requires deeper cells and well-drained in-situ soils which may not be the case for every site.

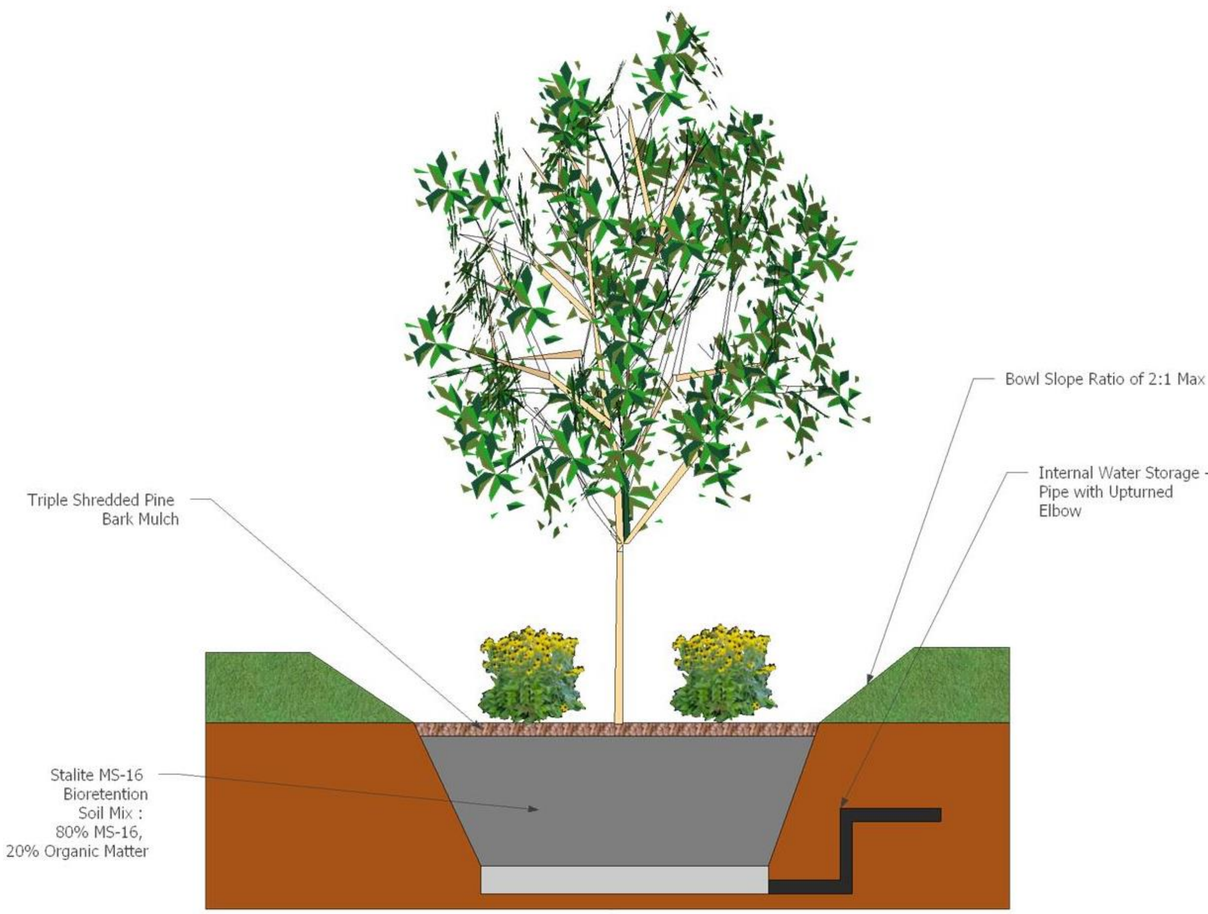


Figure 9 Cross Section of Bioretention Cell Using Stalite MS16 Media and Internal Water Storage (IWS)

Stalite Chemical Properties

Stalite MS16 expanded slate sand has proven to be very effective in remediating stormwater runoff, removing N (nitrogen) and P (phosphorus) better than either the sand or soil based substrates evaluated at NCSU from 2011- 2012.

Table 4 Saturated Media Extract Analysis of USGA Sand and Stalite Sand

Saturated Media Extract Analysis				
Analysis	**Units**	**Result**		**Desirable Range**
		USGA Sand	**Stalite Mix**	
Soluble Solids	mmhos/cm	1.01	1.27	0.4 - 0.8
Nitrate-N (NO_3–N)	mg/L	0.1	3.2	1 - 4+
Ammonia-N (NH_4–N)	mg/L	0.08	0.04	0.4 - 1.5+
Nitrate N + Ammonia-N	mg/L	0.1	3.3	1.4 - 4
Phosphorus (P)	mg/L	0.2	<0.1	2.2 - 5+
Potassium (K)	mg/L	1	16	7.5 - 20+
Calcium (Ca)	mg/L	6	485	40 - 180
Magnesium (Mg)	mg/L	2	5	10 - 55+
Boron (B)	mg/L	0.01	0.1	0.04 - 0.2+
Copper (Cu)	mg/L	0.1	0.4	0.5 - 3
Iron (Fe)	mg/L	1.8	5.2	15 - 40+
Manganese (Mn)	mg/L	0.2	2.3	1 - 4+
Sodium (Na)	mg/L	3	26	0 - 20
Zinc (Zn)	mg/L	0	0.2	1.2 - 10

Analyzing the extraction concentrations of certain elements allows for the prediction of how a sand media will perform in saturated conditions. The results from the analysis above are relevant and can be interpreted in the following ways:

- Though salt levels within the range of 0.8 to 3.0 mmhos/cm may not be toxic, it may indicate potential for nutrient runoff. Salt levels greater than 3.0 mmhos/cm may negatively influence plant growth.
- Though Nitrate-N levels may fluctuate throughout the year due to environmental changes, particularly in early spring, levels should be maintained close to the desirable range listed during the active growing season.

- High Phosphorus levels, Nitrate-N levels greater than 4 mg/L and Ammonium-N levels greater than 1.5 mg/L may not be toxic but can contribute to nutrient runoff.
- Excess nitrogen encourages weed growth and runoff contamination without improving plant coverage.
- High boron levels are toxic to most plants.
- Though manganese levels in the range of 4 to 17 mg/L and iron levels in the range of 40 to 60 mg/L may not be toxic, those levels can contribute to nutrient runoff. Extraction levels greater than these ranges may impact plant growth.
- Zinc levels greater than 12 mg/L may negatively influence plant growth.

Stalite has a suitable Cation Exchange Capacity (CEC), which provides the ability to fix anionic nutrients, primarily phosphate.

Table 5 Chemical Analysis of Stalite

Coarse Fines Soluble Anions and Cations Report				
Cations	**Concentration (ppm)**		**Anions**	**Concentration (ppm)**
Sodium	19.9		Fluoride	3.8
Ammonium	13.4		Chloride	11.8
Potassium	16.9		Sulfate	89.7
Magnesium	11.1			
Calcium	330			

Physicochemical Characteristics

Stalite MS16 possesses 8% absorption capacity and 21.5me/100g CEC. Additional research to determine Stalite's retention and release rates and the degree to which those characteristics are contributing factors in the remediation of Nitrogen is currently in progress. The CEC and high levels of calcium in Stalite expanded slate could be forming complexes with PO_4 (phosphate) and forming an insoluble precipitate.

pH

Stalite coarse aggregates possess an average pH of 8.0. The MS16 sand pH averages 8.0 to 8.8. When blended with 20% approved organic matter the pH averages is 7.0. The acceptable pH range for nutrient uptake by plants is 5.5-6.5. Research at NCSU indicated that the pH dropped in Stalite media and silica sand media when secondary source pond water enriched with ammonium phosphate was added. However, the Stalite media maintained a pH of 5.3, which is acceptable for plant nutrient uptake. The silica sand media dropped lower to 4.8, which does influence nutrient availability and uptake by plants.

Heavy Metals & Toxic Materials

Stalite MS16 is sterile and inert. All impurities are eliminated during the heating process. There are certain procedures with standards set by the EPA to determine the level of toxicity of soil substrates.

Heavy metal analysis of Stalite MS16 was conducted in December 2011 via the Method 7470A as given by the EPA. Method 7470A is a which is a cold-vapor atomic absorption spectrometry (CV-AAS) procedure approved for determining the concentration of mercury in mobility-procedure extracts, aqueous wastes, and ground waters.

The Toxicity Characteristic Leaching Procedure (TCLP) is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes. The test most commonly applies to landfill applications but is relevant in bioretention applications due to the similarities of the leaching process in both. The results from a previous TCLP Analysis are given in the table below.

Table 6 TCLP Analysis

Toxicity Characteristics Leaching Procedure Analysis	
TCLP	**Result (mg/L)**
Arsenic	< 0.01
Barium	0.06
Cadmium	< 0.01
Chromium	< 0.01
Lead	0.03
Selenium	< 0.01
Silver	< 0.01
Mercury	< 0.002

Stalite Bioretention Media Specification

Specifications

Below is a specification of Stalite MS16 Bioretention Media available for use. This Specification section can be found electronically on the Permatill website (www.permatill.com).

SECTION 329120 – Stalite Bioretention Media

PART 1 - GENERAL

1.1 RELATED DOCUMENTS

A. Drawings and general provisions of Contract, including General and Supplementary Conditions and Division-1 Specification sections apply to work of this section.

1.2 SUMMARY

A. Section Includes:

1. Components in the Bioretention Media

B. Related Sections:

1. Section 312000
2. Section 319100
3. Section 329300
4. Section 334600

1.3 DEFINITIONS

A. Finish Grade: Elevation of finished surface of planting soil.

B. Manufactured Media: Soil produced off-site by homogeneously blending mineral soils or sand with stabilized organic soil amendments to produce bioretention media.

C. Expanded Lightweight MS16 Sand: Manufactured sand graded from the screenings of crushed expanded slate.

D. Subgrade: Surface or elevation of subsoil remaining after excavation is complete or top surface of a fill or backfill before the bioretention media is placed.

E. Subsoil: Usually all soil beneath the topsoil layer of the soil profile, and typified by the lack of organic matter and soil organisms.

F. Surface Soil: Soil that is present at the top layer of the existing soil profile at the Project site. In undisturbed areas, the surface soil is typically topsoil, but in disturbed areas such as urban environments, the surface soil can be subsoil.

1.4 ACTION SUBMITTALS

A. Product Data: For each type of product indicated.

1. Stalite Bioretention Media: Include product label and manufacturer's installation instructions specific to this Project.

Carolina Stalite Company 800-898-3772 www.permatill.com

1.5 INFORMATIONAL SUBMITTALS

A. Qualification Data: For qualified Installer.

1. Material Test Reports: For bioretention media

B. Submit manufacturer's technical product data and certified laboratory test results for the following:

1. Stalite MS16 Lightweight sand gradation

C. Sample: Provide one (1) quart of Stalite Bioretention Media in heavy duty clear re-sealable plastic storage bags labeled, "Bioretention Media", and the type and the project name.

1.6 QUALITY ASSURANCE

A. Provide the bioretention media prepared by a blender approved in the production of the specified items.

B. Pre-installation Conference: Conduct at the Project site.

1.7 DELIVERY, STORAGE AND HANDLING:

A. When stockpiling finished bioretention media blend, place on a paved or protected base to prevent contamination.

B. Do not deliver or place soil in frozen, wet, or muddy conditions.

PART 2 – PRODUCTS

2.1 GENERAL PRODUCT REQUIREMENTS:

A. Provide a Bioretention media using the two components listed below measured by volume as follows:

1. Stalite MS16 Lightweight Sand 80% by volume
2. Approved organic components 20% by volume
    a. Percentages of sand and organic may vary to meet test requirements.
    b. The blended media shall have organic matter content between 3% and 5% by mass determined using ASTM F1647 Method B.

B. Source: Carolina Stalite Company, Salisbury, NC (877) 737-6284, www.permatill.com

C. Compaction: When calculating the volume necessary for the project, add approximately 22% to the calculated volume to allow for compaction necessary to meet infiltration rate and specified depth. One cubic yard of Stalite MS16 80:20 Bioretention Media weighs 0.78 tons dry loose.

2.2 BIORETENTION MEDIA COMPONENTS:

A. Stalite Expanded Slate Lightweight sand gradation MS16

1. Unit Dry Weight loose: 53 lb./c.f. to 58 lb./c.f. (ASTM C29)
2. Gradation: MS16

Sieve Size	**% Retained**	**% Passing**
#4	0-3	97-100 %
#8	0-11	89-100 %
#16	34-45	55-66 %
#30	59-72	28-41 %
#50	75-83	17-25 %
#100	84-92	8-16 %
#200	88-92	8-12 %

B. Organic Component

1. Aged pine bark fines screened to minus ½"
2. For Stalite Environmental quality control, compost shall not contain any manure products or municipal biosolids
3. Compost shall be screened to minus 3/8"
4. Organic component shall have total N of ≤ 2% of dry weight.
5. Organic component shall have P (P2O5) of ≤ 1% of dry weight.
6. Organic component salt content shall be < 10 millimho/cm at 25 ° C (ECe <10) on a saturated paste extract.
7. Organic component metals and contaminants must fall within US EPA Standard 40

2.3 BIORETENTION MEDIA PERFORMANCE STANDARDS

A. Initial Laboratory Testing:

1. Phosphorus Index (PI) of the blended media shall fall between 10 and 30 (NCDA)
2. Permeability at Constant Head ASTM D 2434: 4 to 6 inches per hour
3. Hydraulic Conductivity ASTM D 5084: 2 to 6 inches per hour
4. Phosphorous (PO_4): Removal: ≥ 60%
5. Nitrogen (NO_3): Removal: ≥ 60%
6. Total Suspended Solids (TSS): ≥ 85%

PART 3 - INSTALLATION GUIDELINES

3.1 INSTALLATION

A. Erosion Control

1. Always follow local water quality guidelines to prevent sediment accumulation in or around the bioretention installation. Proper erosion control devices and groundcover must be in place before finalizing the installation of the rain garden.

B. Placing and Compacting Bioretention Media:

1. Contain and protect the Bioretention Media to prevent contamination or segregation of components if stock piling on site before placement.
2. Place the Bioretention Media in horizontal lifts not exceeding 12 inches depth. Compact each lift using a vibratory plate compacting machine. Perform 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 should the field engineer determine additional compaction is necessary to insure stability of the layer. Continue placing and compacting 12 inch lifts until the specified depth is reached. For large spaces, a vibratory steel roller weighing no more than 12 tons static weight can be used. Horizontal lifts should not exceed 12 inches compacted. The minimum number of passes is two and maximum number is four. Additional passes may be required should the field engineer determine that additional compaction is necessary to insure stability of the layer.

3.2 PLANTING

A. Plant per drawings and specifications

1. When tree, shrub and perennial planting is specified, add a 1 to 3 inch layer of triple shredded aged hardwood mulch to reduce substrate surface temperature, retain moisture, slow down infiltration, and capture heavy metals.

2. Sod installation requires a sand base sod. Place sod directly on the bioretention media and irrigate until established.

3.3 MAINTENANCE

A. Follow state guidelines for maintenance practices, including but not limited to pest management, watering newly planted plant materials, pruning, erosion and sediment control, raking and replacing mulch, debris clean up, weeding and periodic soil testing. Even the most porous soils can clog from accumulated debris and sediment.

B. Broom clean paved areas and cover stockpiled material after each day's operation.

END OF SECTION 329120

Water Release Characteristics

Stalite MS16 sand has consistently exhibited greater hydraulic conductivity than silica sand. This is due, in part, to the angular shape of Stalite sand particles as well as a higher percentage of those sand particles being in the medium size range of 2.00-0.50 mm. High hydraulic conductivity is not necessarily a negative design factor in bioretention design. However, by adding 20% by volume of organic matter to Stalite MS16 for a bioretention media significantly increases moisture absorption and retention and slows down hydraulic conductivity.

"In comparison to typical, natural occurring mineral aggregates, expanded materials are distinguished by unique fluid absorption characteristics. A study completed by Carolina Stalite Company in 2006 determines that most moisture retained by expanded slate aggregate is present in a shallow field of pores in a zone close to the particle surface. Because the pore network is largely unconnected, only the exterior pores and interior pores connected by micro cracks and fissures fill with fluid. These features result in Stalite expanded aggregates having higher absorption capacity than typical normal weight aggregates, but less absorption capacity than materials with linked pore networks. The absorption rate is initially rapid, and then reduces in magnitude over a period of 120 hours." (Moisture Dynamics of Expanded Slate Lightweight Aggregate 2006. Carolina Stalite Company 2006)

Soil Media Depths

Media depth recommendations are determined by specific site needs and by the vegetation it will be supporting. Grassed cells should have a minimum depth of 2 feet. Mixed woody and herbaceous cells should be 3 feet deep. Bioretention cells designed with IWS zones should have a minimum depth minimum of 3 feet.

Estimating the Amount of Media Needed by Weight

Add 22% to your media volume calculations to allow for settling and compaction to meet the specified filter depth. One cubic yard of Stalite MS16 80:20 bioretention media weighs 0.78 tons.

Availability

All Stalite engineered soils are manufactured, blended, and then shipped from our facility in Norwood, NC. Our central east coast location offers easy access to highways and railways. We maintain distribution terminals in the eastern U.S. where we have approved blenders equipped to service clients in their location. Carolina Stalite Company also has access to terminals throughout the country.

Research Project Profiles

North Mecklenburg Recycling Center - Huntersville, NC

Infiltration and Physical Filtration Testing

The resistance to clogging and physical filtration capabilities of Stalite MS16 was observed at a side-by-side bioretention project constructed at the North Mecklenburg Solid Waste Recycling Center in Huntersville NC.

Figure 10 Installation of Bioretention Cells at North Mecklenburg Solid Waste Recycling Center – Huntersville, NC (July 2009)

Identical grassed bioretention cells were separated by a berm and filled with different substrates in July 2009. One cell contained the standard Charlotte -Mecklenburg Bioretention Soil Mixture that contains 80% by volume of washed sand, 15% by volume of a silt/clay mix, and 5% by volume of compost. The other cell contained a Stalite media that consisted of 80% by volume of Stalite MS16 and 20% by volume compost. Sand-based Bermuda sod was installed over both cells in July 2009 with temporary irrigation for root establishment.

Figure 12 Post Installation Photo Bioretention Cell at North Mecklenburg Solid Waste Recycling Center - Huntersville, NC (August 2009)

The Charlotte–Mecklenburg bioretention media was designed to infiltrate at a rate of 2 inches per hour. When rainfall events caused an overflow from the fore-bays into both of the cells, the resultant sedimentation slowed the infiltration rates. This sedimentation caused extended ponding in the Charlotte-Mecklenburg mix that eventually caused the Bermuda turf to decline. Sedimentation also had an adverse effect on the infiltration rates in the Stalite MS16 mix, however it did not impede the root zone from draining the excess of water and from aerating.

Figure 11 Post Installation Photo of Bioretention Cell at North Mecklenburg Solid Waste Center-Huntersville, NC (October 2009)

Charlotte-Mecklenburg Stormwater Services conducted jar sample collections for a visual assessment of performance during spring 2010. The jar test is used predominately to visually assess the removal of Total Suspended Solids (TSS).

Figure 13 (From left) Charlotte Mecklenburg Bioretention Soil Mix Influent & Effluent; Stalite Bioretention Media Influent and Effluent (2010)

The Charlotte-Mecklenburg media was removed in 2011 and replaced with Stalite media. Today, both cells are now functioning well. For additional information on this active BMP, contact the Charlotte-Mecklenburg Stormwater Services (www.charmeck.org).

Hospice of Wake County - Raleigh, NC

Infiltration and Physical Filtration Testing

The bioretention project at the Hospice of Wake County was a design-construction project in Raleigh, NC by Mike Ruck of Rain Water Solution and Ryan Smith, PE of Water Oak Engineering. The purpose of this project was to collect all stormwater runoff from the impervious surfaces of the Hospice site, treat and reclaim that water, and reuse it to help meet the irrigation needs at the facility. To meet the capacity requirements of such a system, a 50,000-gallon cistern was installed underneath the originally permitted dry detention pond.

Figure 14 Installation of Bioretention Cell at the Hospice of Wake County- Raleigh, NC (March 2010)

Figure 15 First Flush Capture from Cistern at Hospice of Wake County - Raleigh, NC (2010)

A bioretention media filter was constructed at the base of the pond, directly above the subterranean cistern to filter and treat stormwater runoff before it enters into the cistern through the top of the tanks. A mixture of Carolina Stalite MS16 was selected because of its ability to infiltrate water at a high rate. The cistern was constructed from modular blocks called 'Rain Tanks' and was designed specifically to handle high dead loads.

The benefits and overall goals of this project was to greatly reduce runoff volumes leaving the site, reduce pollutant export, and reduce municipal water consumption by way of successfully harvesting a vast majority of stormwater runoff volume. Particular design elements of the dry detention pond were installed in order to improve surface storage over the cisterns and technically improve the peak flow mitigation within the pond.

Figure 16 Hospice of Wake County Bioretention Cell with Bermuda Turf Overlay - Raleigh, NC (Summer 2012)

NCSU Rain Garden Trials

Remediation of Urban Stormwater Pollution by Three Different Filter Substrates and Plant Effectiveness in Pollution Sequestration

Researchers: Rebecca L. Pledger, Dr. Helen T. Kraus and Dr. Ted E. Bilderback, Department of Horticultural Sciences, North Carolina State University, Raleigh, NC

Objective:

Twelve identical cells, 6 feet wide by 32 feet long by 4 feet deep in dimension, were constructed to analyze the effectiveness of three different bioretention substrates and sixteen species of plants in pollution sequestration of urban stormwater runoff for eighteen months.

Figure 17 NCSU Rain Garden Trials - June 2011

Substrates

There were three different substrates that were installed into four cells; a sand, soil, and Stalite based bioretention media. The sand based mixture included 80% by volume of washed sand, 15% clay and silt fines, and 5% pine bark with a P-index of 5 per NC DENR recommendation. The soil based bioretention media included 50% sandy loam soil and 50% pine bark with a P-index of 24.5. The Stalite based bioretention mediature included 80% Stalite MS16 and 20% pine bark with a P-index of 23.

Irrigation source

A lined irrigation pit was installed in the center of the twelve rain garden cells. Irrigation water was pumped from a local urban stormwater (secondary source) runoff pond. While the pit was being filled, 50 mg/L N (supplied by dissolved ammonium sulfate, 21-0-0) and 50mg/L P (supplied by dissolved diammonium phosphate 18-46-0) were added to the irrigation pit. Volume and frequency of irrigation water applied to all rain gardens were identical and recorded. A water sample were grabbed from the irrigation pit before and after fertilizer was added. Samples were then grabbed from each of the twelve rain gardens after each irrigation event.

The leachate catchment pipe for each rain garden terminated into a bucket. From each bucket, samples were collected from each rain garden after each irrigation event for every other week. However, during the dormant season samples were taken monthly. Samples were frozen prior to being submitted for testing at NCDACS.

Results

Figure 18 NCSU Rain Garden Trials June 2012

Infiltration Rate

Season One 2011: At the beginning of the season, the MS16 media infiltration rate was slower than that of the soil media, and quicker than that of the sand media. At the end of season one, the MS16 media had the quickest infiltration rate; possibly due to the faster growth of roots in the Stalite MS16 media.

Season Two 2012: The MS16 media and the soil media had similar infiltration rates that were faster than that of the sand media.

Hydraulic Conductivity and Moisture Content

Under saturated conditions water moved slowest through than that of the sand media quickest through the soil media. This is most likely due to the sand's greater percentage of larger particles and the soil's percentage of small particles.

Moisture content, after drainage, was greatest in the soil media. Moisture contents after drainage of the sand media and the Stalite MS16 media were not different from each other even though the saturated hydraulic conductivity between these substrates were significantly different. Sand media and MS16 media had similar total percentages of fine particles.

Bulk Density

Bulk Density was the greatest in the sand, followed by Stalite MS16 and then the soil, in that order.

Chemical Properties of Leachate

Nitrogen

Even though N concentration applied to the simulated runoff water was consistent throughout the study, N concentration in the leachate varied.

Season One 2011: As plant roots were establishing the N concentrations in sand media averaged 30.1 mg/L. Stalite MS16 and soil media both averaged 17mg/L.

Season One 2011 (Dormant): Nitrogen concentrations of sand averaged 13mg/L while the soil and Stalite MS16 averaged 8mg/L.

Season Two 2012: When plants were well rooted there were fewer differences between substrates and N concentrations, which averaged approximately 10mg/L.

Phosphorus

For 60% of the irrigation events, the substrate affected Phosphorus concentration in the effluent. The soil substrate generally had higher concentrations of Phosphorus in the leachate throughout the study. For 54% of the rain events where substrate affected Phosphorus concentration in the leachate, the sand and soil were not significantly different from each other.

Season One 2011 (including dormant season): Stalite MS16 bound significantly more P, reducing P concentrations in the leachate by 90% on average.

Season Two 2012: Phosphorus in the leachate varied with time. The Sand and soil substrates maintained levels approximately 3mg/L, while the Stalite MS16 substrate levels were approximately 1mg/L. Plant uptake of the Phosphorus appeared nearly equal to the Phosphorus concentrations in the simulated runoff as the Phosphorus concentrations in the leachate decreased.

Figure 19 The harvesting of roots grown in the Stalite Rain Garden Mix for two seasons in July 2012

Substrate Temperature

All substrates maintained temperatures above air temperature except in the early mornings. Sand and soil had the smallest swing in temperature in a day due to their higher moisture content. Maximum temperatures of Stalite MS16 were significantly greater than sand or soil. Possibly, the application of mulch would reduce substrate temperature.

Vegetation and Plant Growth

All of the tree and shrub species grew well in all substrates. Itea virginica did exhibit transplant stress possibly caused by high substrate temperatures which can be a problem with MS16 heat transfer capabilities. Adding a thin surface layer of mulch or other ground cover will alleviate that issue.

All of the herbaceous perennials and ornamental grasses grew well in all the substrates with the exception of Juncus effuses 'Frenzy' which died in all three trial cells.

In the table below, a list of the plants that were used in the 12 trial cells are listed.

Table 7 NCSU Rain Gardens Growing List

NCSU Rain Garden Trials List of Native (N) and Cultivar (C) Plant	
Trees and Shrubs	**Herbaceous Perennials and Ornamental Grasses**
Magnolia Virginia (N)	Helianthus angustifolius (N)
Magnolia Virginia L. 'Sweet Thing' (C)	Helianthus angustifolius 'First Light'(C)
Betula nigra (N)	Eupatorium purpureum subsp. maculatum (N)
Betula nigra L. 'Duraheat' (C)	Eupatorium purpureum subsp. maculatum 'Gateway' (C)
Viburnum nudum (N)	Panicum virgatum (N)
Viburnum nudum L. 'Winterthur'(C)	Panicum virgatum 'Shenandoah' (C)
Itea virginica (N)	Juncus effusus (N)
Itea virginica L. 'Henry's Garnet'(C)	Juncus effusus 'Frenzy' (C)

UNC Charlotte Column Testing

Phase I: Stalite Pollutant Removal Capacity Evaluations with Simulated Stormwater

UNC Charlotte Environmental Assistance Office, IDEAS Center Jy Wu, Ph..D., Brett Tempest, Ph.D., Regina Guyer, P.E., Emily Chien, X. Liu (February 2012)

Objective

This entire research project was divided into two phases. The Phase I research objective was to provide the initial evaluation on the viability of Stalite MS16 materials for implementation as substrate in BMPs and its influence on filtration, root zone and water quality. A series of experiments were completed using small bench scale columns to determine the influences of MS16 on Nitrogen (NO_3–N) and Phosphorus (PO_4–P) removal.

Phase I Protocol

Bench–scale glass columns at the height of 14 inches were packed with 100% Stalite MS16. Batch column testing was conducted with a synthetic stormwater solution made of Deionized water enriched with 1.0 mg/L (NO_3–N) and 3.33 mg/L(PO_4–P) with a pH range of 5 to 7. A total of 30 test runs were completed.

Figure 20 UNC-Charlotte Phase 1 Column Testing (2011-2012)

Results

Phosphorus remained in the pore water (the water trapped on the outer pores of the Stalite MS16 sand) at the end of each working day and appeared to be gradually removed within the pore water due most likely to pore diffusion. The cumulative removal of (PO_4–P) was 2.42 mg as compared to an inflow cumulative mass of 4.1 mg; yielding an overall removal of 58% or <0.01 mg/g adsorption capacity based on the experimental data from the 30 test runs.

Effluent (NO_3–N) concentration reached a steady level of 0.8mg/L, implying a 20% attenuation of the influent (NO_3–N) concentration.

UNC Charlotte Column Testing

Phase II: Pollutant Removal Capacity Evaluations with Simulated Stormwater

UNC Charlotte Environmental Assistance Office, IDEAS Center Jy Wu, Ph..D., Brett Tempest, Ph.D., Regina Guyer, P.E., Emily Chien, X. Liu (November 2012 –March 2013)

Objective

The objective of Phase II of the BMP viability project was to provide an evaluation of Stalite MS16 properties and allow for determination of the leaching effects and nutrient removal. This phase included columns loaded with other bioretention media designs to observe similarities and differences in performance of nitrogen (NO_3–N) and phosphorus (PO_4–P) removal.

Phase II Protocol

Four larger scale columns with a 6-inch diameter were used containing 12 inches of bioretention media. The bioretention media was packed over a screened gravel layer. 100-150 ml of synthetic stormwater samples consisting of Deionized water enriched with 1.0 mg/L(NO_3-N) and 3.33 mg/L(PO_4-P) were applied for chemical analysis. The columns were infiltrated via two different infiltration techniques; the batch feed and gravity flow methods. The batch feed infiltration method, which used in Phase I, was applied to Columns 1 and 2. The gravity flow method requires that the drain valves be closed for 30 minutes prior to outflow, allowing the feed water to slowly penetrate into the column. This method was applied to columns 3 and 4.

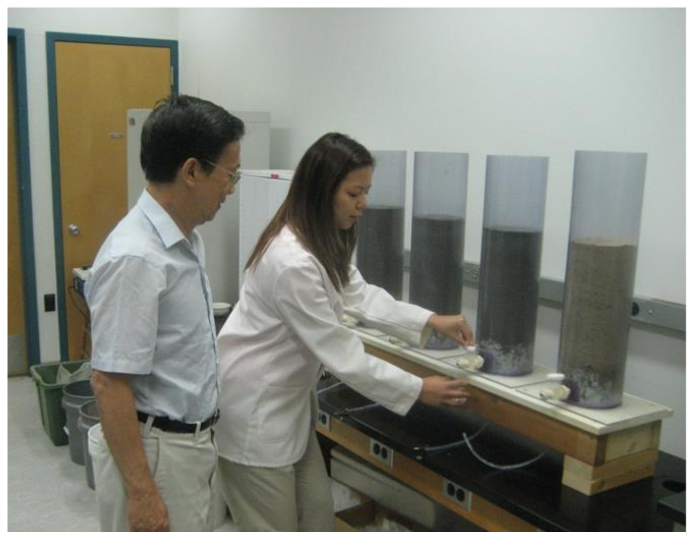


Figure 21 UNCC Phase II Column Testing with Dr. Jy Wu and Emily Chien

Results

Phase II research began November 2012 and concluded February 2013 with 117 test runs being conducted.

Table 8 UNC-Charlotte Column Testing Results

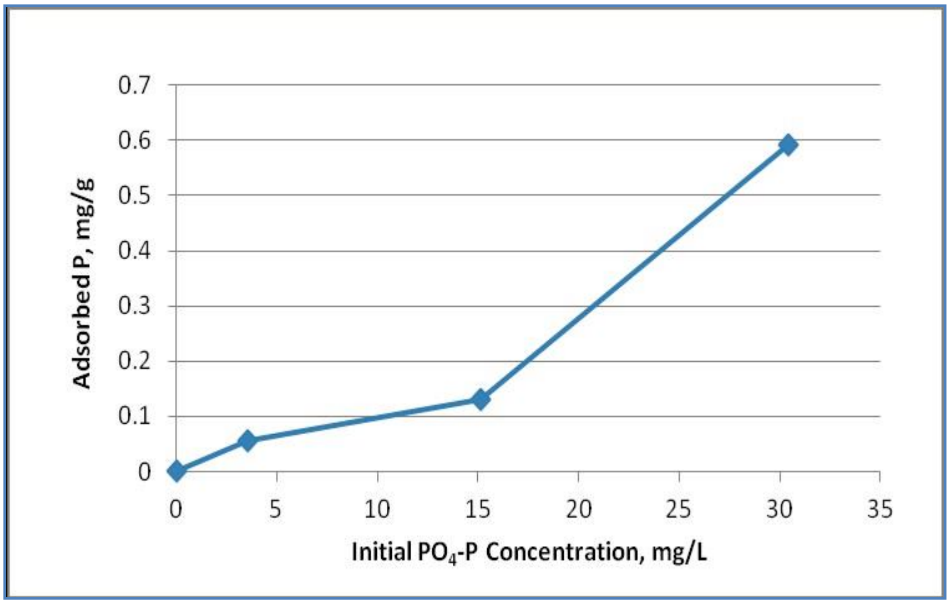
UNC-Charlotte Column Testing Results								
Column No.	Contents	Infiltration Method	Nitrogen Treatment (NO_3-N) in mg/L			Phosphorus Treatment (PO_4-P) in mg/L		
			Influent	Effluent	Reduction	Influent	Effluent	Reduction
1	80% MS16 Stalite Sand, 20% Organics	Batch Feed	1	0.3	70%	1	0.35	65%
2	100% MS16 Stalite Sand	Batch Feed	1	1	0%	1	0.1	90%
3	100% MS16 Stalite Sand	Gravity Flow	1	1	0%	1	0.2	80%
4	80% Silica Sand 15% Clay-Sand Mix 5% Organics	Gravity Flow	1	0.3	70%	1	0.96	4%

Although this study only lasted 4 months and was conducted in a laboratory setting that tested media depths of only 12", the data collected indicates that MS16 is viable alternative to traditional BMP soil mixes where nitrogen and phosphorus loads are primary considerations. Due to the physical characteristics of Stalite MS16, 80-90% of Phosphorus was removed versus the 4% removal rate of Silica Sand based mix. The lack of organic matter in the 100% Stalite columns makes it impossible to treat nitrogen.

Additional Batch Adsorption Experiment with Agitation

A batch adsorption test evaluated the effect of agitation in improving the adsorption capacity by minimizing film diffusion. The experiment consisted of placing 1 gram of Stalite MS16 in 100 mL of synthetic stormwater with 4 different levels of $(PO_4–P)$ concentration. The contents were mixed with a magnetic bar for a period of 24 hours. Results demonstrated that adsorption capacity of Stalite MS16 increases linearly with increasing equilibrium concentration. Those results are shown in the table below.

Table 9 Initial versus Adsorbed Concentration of Phosphorus in mg/g of Agitation Results



Stalite Bioretention Project Profiles

Grassed Bioretention Cells

Graham High School – Graham, NC

Figure 22 Excavation of two Bioretention cells (2005)

This project was designed and monitored by the NCSU BAE Department to monitor the performance of cells constructed with internal Water Storage (IWS) zones. The two grassed bioretention cells installed at Graham High School in 2005 were unique due to their selection of turfgrass as a vegetated cover. Both cells were constructed with an IWS zone and varied by soil depth and underlying in-situ soil type. The cells were not lined. The bioretention media contained 80% Stalite MS16 which provided a large amount of pore volume and a high infiltration rate. Water quality samples were collected from April 2006 to October 2006. Nutrient load reductions for Nitrogen were approximately 70-80% range while Phosphorus load reductions were in the 35-50% range.

Figure 23 Sand Based Bermuda Sod placement (2006)

Figure 24 Cell in place (2010)

CKS Packaging Facility & Borg Warner Corporation - Arden, NC

The turf bioretention cell at the CKS Warehouse in Arden, NC was installed in 2010 to collect, treat and transmit stormwater from the roof of the warehouse. Installed in 2010 and 2011 to collect runoff from the roof of the CKS warehouse. The bioretention cell at the Borg Warner Corporation in Arden, NC receives runoff from adjacent paved parking lot and roof. The turf selected for both projects is Tall Fescue.

Figure 25 CKS Packaging - Arden, NC (2011)

Figure 26 Borg Warner Corporation - Arden, NC (2010)

Baker Exhibit Center at NC Arboretum – Asheville, NC

The Baker Exhibit events lawn area was designed as a load-bearing high infiltrating event turf that also serves as a primary stormwater treatment system. The event turf is designed so that water will infiltrate through the turf, down through the Stalite media and into perforated pipes that drain into the rain garden at the circular arrival area on another part of the property. The load-bearing, high infiltrating event turf media includes a percentage of a coarser Stalite particle ranging from 2.36-4.75mm for durability and long-term porosity. The turf is Tall Fescue.

Figure 27 Baker Exhibit Center Event Turf during installation (2008)

Figure 28 Baker Exhibit Center Event Turf (2012)

Woody & Herbaceous Planted Bioretention Cells

Baker Exhibit Center, NC Arboretum, Asheville, NC

The Baker Exhibit Center Rain Garden collects stormwater runoff from the events lawn (as referenced above) and portions of the building and parking area. Selected plants include Liatris microcephala (Dwarf Blazing Star), Iris virginica (Virginia dayflower), Iris fulva (Miniature Tall Bearded Iris), Viburnum dentatum (Arrowood Viburnum), Panicum virgatum 'Prairie Sky' (Prairie Sky Switchgrass), Juncus effuses (Common Rush), and Hibiscus moscheutos (Swamp Hibiscus).

Figure 29 Baker Exhibit Center, NC Arboretum-Asheville, NC (2012)

Hazelwood Elementary School – Waynesville, NC

Constructed in 2005 to capture stormwater runoff from the school roof and playground, this particular project has excelled in sustaining plant life and in treating the stormwater needs of the drainage area. Vegetation used in this project includes Helianthus angustifolius (Swamp Sunflower), Panicum virginicus (Switchgrass), Itea virginica (Virginia Sweetspire) Showy Goldenrod (Sollidago speciosa).

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Figure 30 Hazelwood Elementary School - Waynesville, NC (2005)

Figure 31 Hazelwood Elementary School - Waynesville, NC (2012)

Transylvania County Public Library – Brevard, NC

In this particular project, these bioretention cells are treating the excess sediments and pollutants prior to entering back into the stream system. Also to note is that these cells, being in the western mountainous part of the state have much deeper depths that what is typically found in the east. Depths can range from 4-6 feet. The drainage area included the runoff from the roof of the library as well as the stormwater runoff from all paved areas. There was an extensive plant list for this project. Vegetation includes Ilex glabra (Inkberry), Iris virginica (Blue Falg Iris),, Hypericum densiflorum (Bushy St. John's-wort), Iris pallid, Eupatorium (Joe-Pye Weed), Hypericum densifolium (Bushy St. John's-wort), Phlox paniculata (Garden Phlox), Magnolia virginiana (Sweetbay Magnolia), Juncus efusus (Soft Rush) and Rudibeckia hirta (Black-eyed Susan).

Figure 33 Curb less Traffic Island Bioretention Cell (2005)

Figure 32 The same Curb less Cell at Transylvania County Public Library - Brevard, NC (2007)

Figure 34 A Roadside Bioretention Transylvania County Public Library - Brevard, NC (2007)

Creative Arts Building at Haywood Community College – Clyde, NC

The rain garden collects stormwater runoff from the playground area of the center and pretreats it prior to infiltration into to native soil. Vegetation includes Iris virginica (Blue Flag Iris), Phlox paniculata (Garden Phlox), Panicum virgatum (Switchgrass), and Tradescantia virginiana (Virginia Spiderwort).

Figure 35 Creative Arts Building at Haywood Community College - Clyde, NC (2012)

Richmond Hill Park – Asheville, NC

This project was installed as part of the French Broad River Watershed Protection Program. Stalite bioretention media in the cell pretreats stormwater runoff before it flows to a larger retention pond for further treatment. Vegetation includes Cercis canadensis (Eastern Redbud), Iris virginica (Blue Flag Iris), Panicum virgatum (Switchgrass), Viburnum dentatum (Arrow-Wood Viburnum), Itea virginica (Virginia Sweetspire), and Acer rubrum (Red Maple).

Figure 36 Richmond Hill Park - Asheville, NC (2008)

Figure 37 Richmond Hill Park - Asheville, NC (2012)

The Read Building – Falls Church, VA

Multiple bioretention cells were installed in this urban setting. The first cell is a 5-foot deep bioretention cell between the Read Building and a gas station. Vegetation includes Acer rubrum (Red Maple), Ulmus “Princeton’ Elm (Princeton Elm), Myrica pennsylvanica (Wax Myrtle), Spirea japonica “Shirobana’, (Shirobana), Spirea), Hemoricallis ‘Hyperion’(Hyperion daylily), and Echinacea purple ‘Crimson Star’(Crimson Star Coneflower).

Figure 38 Bioretention Cell between the Read Building and a Gas Station

Figure 40 Bioretention Cell in a wall at the Read Building -Falls Church VA

The next cell shown is a deep (greater than 5 feet in depth) bioretention wall planter with vegetation that includes Platanus acerfolia ‘Bloodgood’ (Bloodgood London Plane Tree), Ilex crenata ‘Soft Touch’ (Soft Touch Holly), Berberis thunbergii (Japanaese Barberry), Narcissus “Dutch Hood’, and ‘Mount Hood’ (Daffodills).

Figure 39 A close-up of dense vegetation within a bioretention cell at the Read Building

That last two figures show a close up of vegetation within an engineered planting media with coarse Stalite to enhance drainage and aeration. Vegetation includes Hydrangea arborescens ‘Hils of Snow’ (Hills of Snow Hydrangea), Hydrangea macro ‘Forever Pink’ (Forever Pink Hydrangea), Acer rubrum ’Armstrong’ (Armstrong Red Maple) Prunus laurocerasus ‘Otto Luykens’ (Otto Luykens Skip Laurel), Vibrunum utile ’Conoy’ (Conoy Viburnum), Itea viginica ’Henry’s Garnet’) Henry’s Garnet Sweetspire, and Myrica pennsylvanica (Wax Myrtle).

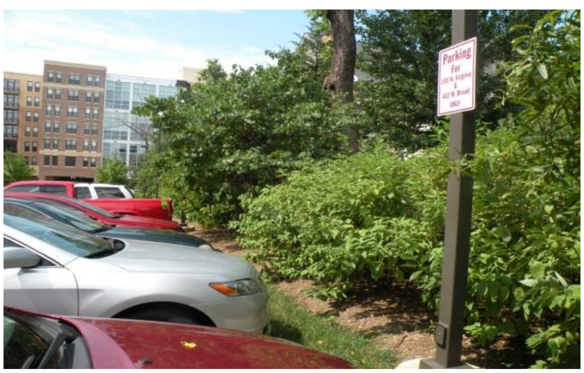

Figure 41 Established Planting at one of the bioretention cells at the Read Building.

Guilford County Cooperative Extension Complex – Greensboro, NC

This rain garden was constructed to receive stormwater runoff from the event barn for primary treatment before filtering into a constructed wetland for further treatment. This project was designed with the protection of South Buffalo Creek. Vegetation includes Rudibeckia hirta (Black Eyed Susan), Hibiscus moscheotus (Swamp Hibiscus), Iris virginica (Blue Flag Iris), Eupatorium purpureum (Joe-Pye Weed), Buddleia (Butterfly Bush), Hemerocalis 'Hyperion' (Hyperion Daylilly), Juncus effuses (Soft Rush).

Figure 42 Guilford County Cooperative Extension Complex - Greensboro, NC (2007)

Figure 43 Guilford County Cooperative Extension Complex - Greensboro, NC (2012)

Alumni Field House at Rhodes Stadium (Elon University) – Elon, NC

The drainage area for this project included the Rhodes football stadium, the Alumni Field House, and the adjacent parking lots. This project was unique in that the vegetation quickly established within the bioretention cell.

Vegetation included Betula nigra (River Birch), Echinacea purpurea (Purple Coneflower), Acorus calamus 'Variagatus' (Variegated Sweet Flag), and Cimicifuga racemosa (American Bugbane).

Figure 44 Alumni Field House at Elon University - Elon, NC (2011)

Figure 45 Alumni Field House at Elon University - Elon, NC (2012)

The Artists Backyard at NC State University – Raleigh, NC

The Artist's Backyard and Owens Refuge is located between Owens and Turlington residence halls at North Carolina State University's Central Campus area. Landscape architecture students completed the concept and design. The project had many focuses such as creating a semi-private outdoor space that is inviting to students and visitors. The primary focus of the project is to of course manage stormwater runoff. The vegetation includes Cercis canadensis (Eastern Redbud), Echinacea purpurea (Purple Coneflower), Rudibeckia fulgida (Black-Eyed Susan), Ilex glabra (Gray Inkberry), Anthyrium feliz-femina (Lady Fern), and Osmunda cinnamoma (Cinnamon Fern).

Figure 46 The Artists Backyard at North Carolina State University - Raleigh, NC (2012) – photo courtesy of NCSU

References

Holm, T. A., and A. J. Valsangkar. Lightweight Aggregate Soil Mechanics: Properties and Applications, *Transportation Research Record 1422,* National Research Council, Washington, D.C., 1993

Carolina Stalite Company. *Moisture Dynamics of expanded Slate Lightweight Aggregate 2006.* Carolina Stalite Company Jody R. Wall, P.E. LEED AP

Petrographic Analysis of Aggregate Stalite Lightweight Aggregate C3S Inc., 2006

Stormwater November, December 2012 'Applying Stormwater Control Measures in Series, The Villanova University treatment train by Cara Lyons, Robert Traver, and Bridget Wadzuk

UNC Charlotte IDEAS Center, Jy S. wu Ph.H., P.E., P.H., Emily Chien, X. Liu Stalite Pollutant Removal Capacity Evaluations with Simulated Stormwater: Phase I & II Report

NCSU, Dept. of Horticulture Science.,R.L. Pledger &Assistant Professor Helen Kraus 2011-2013 *Rain Garden Substrate Research*

Kraus, H., T. Bilderback, R. Pledger, E. Riley, B. Fonteno, and B. Jackson. 2013. Defining rain garden filter bed substrates based on saturated hydraulic conductivity. Proc. Int. Sym. Growing Media and Hydroponics. Ed. A.P. Papadopoulos. Acta Hort. in press.

Websites & Pages

Method 7470A Testing via EPA

http://www.epa.gov/epaoswer/hazwaste/test/pdfs/7470a.pdf

Toxicity Characteristics Leaching Procedure

http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/1311.pdf

Tests & Reports

Turf Diagnostics Turf Diagnostics & Design, August 2011

Analytical Industrial Research Laboratories, Inc., December 2011

Table of Figures

STALITE ENVIRONMENTAL