Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Determining Animal Mortality Compost Maturity and Suitability for Road Project Applications for the Virginia Department of Transportation

http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r21.pdf

BRIDGET M. DONALDSON
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

MICHAEL W. CRAWLEY
Paid Search Analyst
Merkle/RKG

Final Report VCTIR 15-R21

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VCTIR 15-R21	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Determining Animal Mortality Compost Maturity and Suitability for Road Project Applications for the Virginia Department of Transportation		5. Report Date: April 2015
		6. Performing Organization Code:
7. Author(s): Bridget M. Donaldson, and Michael W. Crawley		8. Performing Organization Report No.: VCTIR 15-R21
9. Performing Organization and Address: Virginia Center for Transportation Innovation and Research 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS):
		11. Contract or Grant No.: 105203
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final
		14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

A series of studies on the effectiveness, feasibility, and costs of composting as a means of managing animal mortality removed from roadways has been conducted at the Virginia Center for Transportation Innovation and Research (VCTIR). In these studies, three composting methods were evaluated for use by the Virginia Department of Transportation (VDOT) and found to be effective: static compost windrows, a forced aeration system, and a rotary drum. Successful pilot studies at VDOT maintenance facilities have led to a growing interest in adopting this method of mortality management. As plans for additional composting vessels are underway, final tests are needed in order to develop guidance on composting procedures that generate mature, or finished, compost that is suitable for road project applications.

The purpose of this study was to determine the time and treatment conditions necessary for VDOT compost vessels to generate mature compost and to evaluate the suitability of this compost for potential VDOT applications. Four methods were used to assess compost maturity: temperature monitoring, the Solvita compost maturity test, plant germination and growth tests, and qualitative observations. Tests were conducted on compost generated from the rotary drum and forced aeration system and on compost subsequently transferred to curing areas. The suitability of compost for road project applications was determined by testing compost for a suite of biological, physical, and chemical properties and conducting a demonstration project at a VDOT facility.

Of the compost maturity tests, temperature decline was the most conservative indicator of finished compost. As determined primarily by temperature monitoring and supported by the other maturity tests, compost generated from the forced aeration system and rotary drum should be transferred to curing areas to cure for approximately 8 to 9 weeks. Mature compost generated from these vessels met the U.S. Environmental Protection Agency's compost specifications for transportation applications. It is recommended that VCTIR and VDOT incorporate the findings of this study into a guidance document for VDOT animal mortality composting.

17 Key Words: Animal mortality composting, compost vessels, rotary drum, forced aeration system, compost maturity, compost specifications, compost application	18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 40	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

DETERMINING ANIMAL MORTALITY COMPOST MATURITY AND SUITABILITY FOR ROAD PROJECT APPLICATIONS FOR THE VIRGINIA DEPARTMENT OF TRANSPORTATION

Bridget M. Donaldson
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

Michael W. Crawley
Paid Search Analyst
Merkle/RKG

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

April 2015
VCTIR 15-R21

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

ABSTRACT

A series of studies on the effectiveness, feasibility, and costs of composting as a means of managing animal mortality removed from roadways has been conducted at the Virginia Center for Transportation Innovation and Research (VCTIR). In these studies, three composting methods were evaluated for use by the Virginia Department of Transportation (VDOT) and found to be effective: static compost windrows, a forced aeration system, and a rotary drum. Successful pilot studies at VDOT maintenance facilities have led to a growing interest in adopting this method of mortality management. As plans for additional composting vessels are underway, final tests are needed in order to develop guidance on composting procedures that generate mature, or finished, compost that is suitable for road project applications.

The purpose of this study was to determine the time and treatment conditions necessary for VDOT compost vessels to generate mature compost and to evaluate the suitability of this compost for potential VDOT applications. Four methods were used to assess compost maturity: temperature monitoring, the Solvita compost maturity test, plant germination and growth tests, and qualitative observations. Tests were conducted on compost generated from the rotary drum and forced aeration system and on compost subsequently transferred to curing areas. The suitability of compost for road project applications was determined by testing compost for a suite of biological, physical, and chemical properties and conducting a demonstration project at a VDOT facility.

Of the compost maturity tests, temperature decline was the most conservative indicator of finished compost. As determined primarily by temperature monitoring and supported by the other maturity tests, compost generated from the forced aeration system and rotary drum should be transferred to curing areas to cure for approximately 8 to 9 weeks. Mature compost generated from these vessels met the U.S. Environmental Protection Agency's compost specifications for transportation applications. It is recommended that VCTIR and VDOT incorporate the findings of this study into a guidance document for VDOT animal mortality composting.

FINAL REPORT

DETERMINING ANIMAL MORTALITY COMPOST MATURITY AND SUITABILITY FOR ROAD PROJECT APPLICATIONS FOR THE VIRGINIA DEPARTMENT OF TRANSPORTATION

Bridget M. Donaldson
Senior Research Scientist
Virginia Center for Transportation Innovation and Research

Michael W. Crawley
Paid Search Analyst
Merkle/RKG

INTRODUCTION

VDOT Composting Studies

Virginia has more than 56,000 deer-vehicle collisions along its roadways each year. Removal and disposal of wildlife mortalities cost the Virginia Department of Transportation (VDOT) more than $4 million per year. VDOT's predominant means of managing these mortalities include using disposal facilities (i.e., landfills and transfer stations) and, where possible, burying or setting aside individual carcasses within the right of way. However, many VDOT maintenance facilities face a decreasing availability of landfills and a lack of viable burial areas. These facilities have a need for viable, environmentally compliant, and cost-effective carcass management strategies (Donaldson and Moruza, 2010).

To investigate additional options for managing roadway animal mortality, a series of composting studies was conducted at the Virginia Center for Transportation Innovation and Research (VCTIR) (Donaldson, 2014; Donaldson and White, 2013; Donaldson et al., 2012). The composting of animal carcasses has rapidly spread throughout the United States as an efficient means to manage livestock mortality (Bonhotal et al., 2007). Composting is a natural biological process involving decomposition of organic materials in a predominantly aerobic environment. Composting requires a carbon source or a carbon-rich amendment such as woodchips, sawdust, or wood shavings. A proper balance between the carbon (predominantly from the amendment) and the nitrogen (predominantly from the animal) provides an environment in which the microorganisms responsible for decomposition can thrive (Bonhotal et al., 2007).

In the VCTIR studies, static windrow composting and two types of compost vessels, the rotary drum and the forced aeration system (hereinafter forced air system), were evaluated. Each of these methods was found to be a useful and effective means of mortality management for VDOT (Donaldson, 2014; Donaldson and White, 2013; Donaldson et al., 2012). Static compost windrows are passively aerated static piles and, as such, do not require the materials turning needed with the more traditional covered bin composting method (Figure 1). Analyses of

Figure 1. Three Compost Methods Available for Use by VDOT: Static windrow *(left),* forced air system with a 3-walled covered storage area *(center),* and rotary drum *(right).*

pathogen destruction and leachate constituents in compost windrows found that high temperatures destroyed target pathogens and that nutrient mass loads were lower than typical nutrient loss from fertilizer applications (Donaldson et al., 2012). When left unturned, compost windrows reach maturity in 10 to 11 months (Donaldson et al., 2012).

As mentioned previously, to provide additional composting options that typically have a smaller footprint than windrows and (according to vendors) generate finished or "mature" compost more quickly, the forced air system and the rotary drum (Figure 1) were investigated. Both vessels are designed to aerate the raw material and thereby speed decomposition. Aeration is achieved by automatic rotations (rotary drum) or forcing air through pipes incorporated at the bottom of large containers (forced air system). Aeration supports the aerobic bacteria responsible for decomposition and reduces the formation of odorous volatile anaerobic degradation products that lead to compost phytotoxicity (Rajamäki et al., 2005; Reinhardt, 2002). In the forced air system, leachate drains through holes in the bottom of the containers and collects in a tank; the leachate can then be periodically pumped back onto the material to keep it sufficiently moist. Similar to the findings of the windrow study, compost from the forced air system met established compost criteria (i.e., high sustained temperatures and confirmed pathogen destruction) and the system performed well from an operational standpoint (Donaldson and White, 2013). For the rotary drum, the results of the initial pilot tests were inconclusive with regard to its utility as a means of animal mortality management for VDOT. Using the lessons learned from the initial pilot, a second pilot evaluation of a smaller rotary drum was conducted. In this evaluation, the drum was also deemed successful from a performance and operational standpoint (Donaldson, 2014).

Under the Virginia Solid Waste Management Regulations (VSWMR) (9 VAC 20-81), most animal carcasses are considered a Category IV solid waste. The composting of animal mortality must therefore comply with numerous siting, construction, and testing requirements for solid waste composting (Virginia Register of Regulations, 2011). Over the course of the VCTIR composting studies, VDOT's Environmental Division and VCTIR held meetings with the Virginia Department of Environmental Quality (DEQ), the regulatory agency that enforces these state composting requirements (Virginia Register of Regulations, 2011). The agencies discussed the VCTIR composting research findings with regard to the VSWMR regulations, and the DEQ and VDOT subsequently drafted and signed a memorandum of understanding (MOU) to govern the conditions under which VDOT may perform composting of roadway animal mortality (DEQ and VDOT, 2015). The provisions in the MOU replace the more stringent VSWMR composting requirements. This is expected to increase composting implementation prospects for VDOT and ensure that composting of roadway animal mortalities is protective of human health and the environment.

Compost Maturity

Transportation agencies can use compost for numerous beneficial end uses, including vegetation establishment, site restoration, erosion and sediment control, and soil amendment (Goldstein, 2003). To ensure the suitability of compost for any application, it must first meet pathogen reduction requirements and also be deemed "finished," or mature. *Maturity* is the degree or level of completeness of composting (Composting Council Research and Education Foundation [CCREF] and United States Composting Council [USCC], 2008). To be considered mature, compost should meet certain requirements, but no single test or standard for measuring compost maturity exists (Brinton, 2000; Warman, 1999). In the United States, all waste, including compost, is governed by the U.S. Environmental Protection Agency's biosolids rule (40 CFR Part 503) (U.S. EPA, 2003). This rule, which includes pathogen reduction requirements that apply to compost, has been widely adopted as a de facto compost standard (Brinton, 2000), but it does not address other criteria to assess the quality or maturity of compost.

Because compost maturity is not described by a single property, maturity is best assessed by measuring two or more compost characteristics (USCC, 2010; Warman, 1999). Various measures are used to determine maturity, including temperature decline, the Solvita compost maturity test (hereinafter Solvita maturity test) (Brinton, 2000; Steger et al., 2007), and plant germination and growth tests.

Monitoring the temperature of compost is among the most common means of evaluating the composting process and determining compost maturity (Chen et al., 2011; Haug, 1993). As bacteria, fungi, and other microorganisms break down organic material, they consume oxygen and release heat, water, and carbon dioxide. With proper composting, the heat generated during this process greatly reduces pathogens. The temperature of the compost typically increases rapidly to temperatures above 130° F within 24 to 72 hours after pile formation. Decomposition is most rapid during this "active" phase of composting, which lasts days to weeks depending on the composition of the compost and environmental conditions. A longer curing or maturation phase follows, during which remaining materials continue to decompose (at a slower rate) while temperatures decline (Bonhotal et al., 2007; Chen et al., 2011). Although there is not a national standard in the United States with regard to a compost temperature that indicates maturity or stability, temperature decline to "near ambient conditions" is one of the accepted test methods for determining compost stability in the VSWMR (9 VAC 20-81-340). Canada's compost guidelines (Canadian Council of Ministers of the Environment [CCME], 2005) and findings from an earlier study of animal mortality compost windrows (Donaldson et al., 2012) support the use of particular thresholds of compost temperature above ambient temperature to determine when compost is finished.

The Solvita compost maturity test (Woods End Laboratories, Inc., Mount Vernon, Maine) is another accepted test method included in the VSWMR (Virginia Register of Regulations, 2011) and is widely recognized and validated (Brinton et al., 2012; Steger et al., 2007). This test measures carbon dioxide (CO_2) and ammonia (NH_3) emissions from compost to create a compost maturity index (hereinafter Solvita maturity index). Mature compost emits relatively high levels of CO_2 and low levels of NH_3 (Woods End Laboratories, Inc., 2013). The Solvita maturity index ranges from 1 to 8, in whole numbers. A low index (1-5), which corresponds with relatively low CO_2 and high NH_3 emissions, indicates that the compost is actively degrading and therefore not yet suitable for most applications. A high index (6-8), which corresponds with relatively high CO_2 and low NH_3 emissions, indicates that the compost is aged and ready for application (Woods End Laboratories, Inc., 2013). The VSWMR specifies that compost must have a Solvita maturity index of 6 or higher to be classified as stable and therefore suitable for use (Virginia Register of Regulations, 2011).

Plant germination and growth tests for compost are used to help assess the presence of phytotoxins, which can momentarily or permanently alter plant growth (Baca et al., 1990; Warman, 1999). Mature compost is considered to be nontoxic and to release nutrients for plant growth (Itavaara et al., 2010). Poor plant germination and growth can indicate that the compost is immature (Warman, 1999).

Compost End Use and Characterization

Once criteria such as compost maturity and pathogen reduction have been met, the quality of the compost is dictated by the end use. Because of the environmental benefits of composting, the U.S. EPA promotes the use of compost on state and local roadside applications and funded a report describing the benefits of implementing composting programs within a state department of transportation (CCREF and USCC, 2008). The use of compost has expanded considerably for transportation activities (Alexander, 2003; Goldstein, 2003). Compost blankets, which consist of a 1- to 3-in layer of loosely applied composted material spread on the soil, is one common beneficial use of compost for transportation projects (Alexander, 2003; Glanville et al., 2003). Compost blankets and berms have been found highly effective at reducing erosion and stormwater runoff (Gallardo-Lara and Nogales, 1987; Glanville et al., 2003; Goldstein, 2003).

The American Association of State Highway and Transportation Officials (AASHTO) and at least 31 state transportation agencies have adopted specifications for using compost or related products for roadway applications (Alexander, 2003; AASHTO, 2013a, b). Standards or specifications for compost typically include required values or ranges for a suite of compost parameters, including pH, moisture content, soluble salts, and maximum particle size (Goldstein, 2003). The ideal values for these parameters vary depending on the application. For example, factors such as pH and salt content are important for plant establishment, but these factors are not as critical for erosion control (Goldstein, 2003). The recently signed MOU for VDOT animal mortality composting (DEQ and VDOT, 2015) does not include specification requirements for compost. The AASHTO (2013a, b) and U.S. EPA specifications (CCREF and USCC, 2008) serve as useful (although not mandatory) parameters for compost generated by VDOT.

Final Steps for Composting Implementation

Given the success of the first VDOT composting operations (i.e., two forced air systems in the Lynchburg and Salem districts and one rotary drum in the Staunton District), numerous VDOT maintenance facilities have expressed interest in composting to manage animal mortality. In order to implement composting at additional interested VDOT area headquarters (AHQ), a guidance document is needed that describes the detailed materials, steps, time, and temperature requirements to achieve compost maturity and beneficial applications for the finished compost. In addition, one of the provisions in the aforementioned MOU includes the development of a composting guidance document that will be provided to DEQ for review and comment.

Final pieces of information are needed to develop the composting guidance document. Although research has determined that compost from the static windrows is mature and suitable for application 10 to12 months after windrow construction (Bonhotal and Shwarz, 2009; Donaldson et al., 2012), the time required to compost mortality has not been definitively determined for the forced air system and rotary drum. It has not yet been established, for example, how long the compost material must remain in the forced air system to reach full maturity according to compost tests. For the rotary drum, testing is needed to determine whether compost that emerges from the drum is finished or whether it must subsequently be stored in a curing area to finish maturing. In addition, verification is needed that compost generated from VDOT compost vessels meets relevant compost specifications and can therefore be used for beneficial transportation applications.

PURPOSE AND SCOPE

The purpose of this study was to determine the time and treatment conditions necessary for VDOT compost vessels to generate mature compost from animal mortality and to evaluate the suitability of this compost for potential VDOT road project applications. To achieve this purpose, tests were conducted on compost generated from a forced air system and a rotary drum and on compost subsequently transferred to curing areas.

Four methods were used to assess compost maturity: temperature monitoring, the Solvita maturity test, plant germination and growth tests, and qualitative observations. The suitability of compost for road project applications was determined by testing compost for a suite of biological, physical, and chemical properties and conducting a demonstration project at a VDOT facility.

The scope of the study was limited to compost generated from a forced air system at VDOT's Bethel AHQ and from a rotary drum at VDOT's Fishersville AHQ. Compost generated from the forced air system and the rotary drum was monitored over the course of 18 weeks and 42 weeks, respectively.

METHODS

The following tasks were conducted to achieve the study objectives:

1. Conduct compost maturity tests of compost generated from the forced air system at VDOT's Bethel AHQ.

2. Analyze the collective results of these tests to provide an overall assessment of the time and treatment conditions necessary for compost generated from the forced air system to mature.

3. Conduct compost maturity tests of compost generated from the rotary drum at VDOT's Fishersville AHQ.

4. Analyze the collective results of these tests to provide an overall assessment of the time and treatment conditions necessary for compost generated from the rotary drum to mature.

5. Evaluate the suitability of finished compost from the two AHQs for road project applications by conducting compost characterization tests and demonstrating a beneficial use of finished compost at a VDOT facility.

Compost From Forced Air System

Overview

The compost evaluated for this part of the study was generated from a forced air system at VDOT's Bethel AHQ in Halifax County (Figure 2). This system, constructed by the vendor with temporary rolloff containers for the purpose of a previous pilot study (Donaldson and White, 2013), has been operational since February 2012.

Figure 2. Pilot Forced Air System at VDOT's Bethel Area Headquarters

Each container measures 8 ft by 16 ft by 6 ft and has a capacity of 10,000 lb. Given the success of the pilot study, numerous VDOT AHQs have requested a forced air system. The new designs include larger concrete structures and a separate covered storage or curing area as pictured in Figure 1.

With forced air composting, compost material as young as 6 weeks of age is routinely removed from its original container, mixed in equal parts with sawdust, and used as a carbon source for new mortalities in an adjacent container (as per the vendor's instruction). The use of this "hot" compost expedites the degradation of new mortalities, as it contains a high concentration of microorganisms responsible for decomposition (K. Warren, personal communication). Despite the reuse of the compost material, however, the containers must eventually be emptied to make room for new mortalities. Once removed from the container, the compost is temporarily stored in a curing area. In this report, "curing areas" refer to mounds of composting material with the same dimensions as windrows (as pictured in Figure 1), as detailed by Donaldson et al. (2012), but that comprise material that has already undergone the first stage of composting (i.e., complete or near complete soft tissue degradation). The experimental design for determining the maturity of compost accounts for the varying "treatments," or length of time the composting material might remain in a container before it is removed and stored to provide space for new mortalities.

Only one of the three forced air containers at VDOT's Bethel AHQ was used for this study in order to allow the continued use of the other containers by the AHQ staff. The container was equally divided into three sections with wooden partitions. To determine the time required for compost to mature, composting material remained in each section for varying durations. Compost in Section A remained in the forced air container for the entire 18-week test period, and material in Sections B and C was removed after 9 and 6 weeks, respectively, and transferred to separate curing areas for the remainder of the 18 weeks (Figures 3 and 4). This design also allowed the researchers to determine the treatment that most quickly resulted in finished compost.

Loading each of the three experimental sections was done in accordance with the vendor's operational manual, and each section was layered from the bottom as follows: 12 in of sawdust; 3 or 4 deer mortality placed side by side; and a 4- to 6-in layer of "hot compost" (approximately 8 weeks of age) taken from an adjacent container. Layering continued until there were three layers of deer mortality. Sections were capped with another 12-in layer of sawdust. Each section comprised 8 to10 deer mortality and two temperature data loggers that recorded the temperature every hour; loggers were centered between the first and second and the second and third mortality layers (Figure 3). Each section was filled within 5 days after the first mortality was loaded.

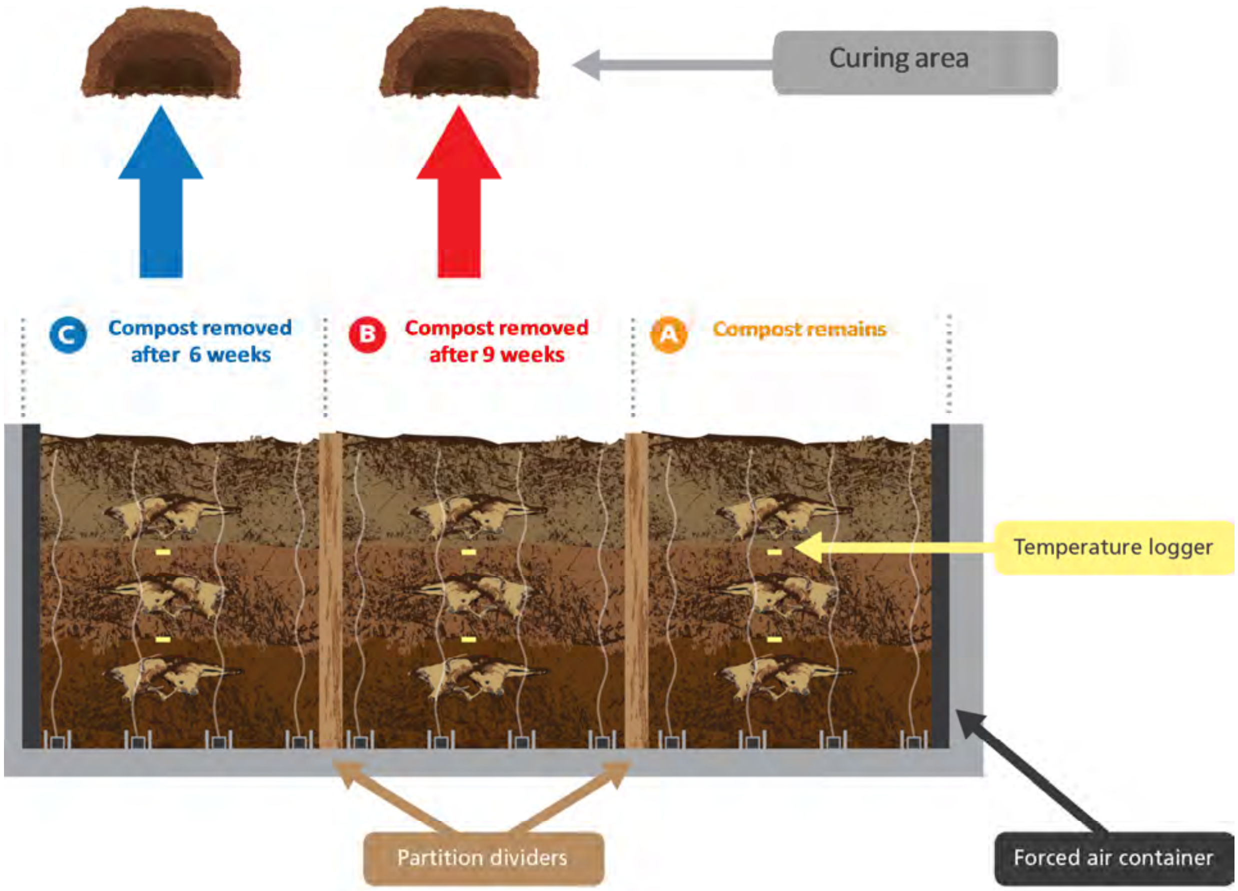


Figure 3. Side View of Three Experimental Treatments (Sections A, B, and C) of Material Composting in Forced Air Container. The illustration is not to scale and underrepresents the number of deer mortality in each section.

Figure 4. Curing Area With Compost From Forced Air System, Section C

Compost Maturity Tests

Compost maturity tests for each section were conducted over the course of 18 weeks (Table 1). Temperature monitoring was continuous, and Solvita maturity tests and qualitative observations were conducted every 3 weeks, beginning at 6 and 9 weeks when Sections A and B, respectively, were transferred to a curing area and when Section C had aged for 12 weeks. No samples were collected from Section C prior to week 12 in order to minimize disturbance. Plant tests were conducted only once on compost from Section A (6 weeks in the container, 0 weeks in curing area); Section B (9 weeks in the container, 0 weeks in curing area); and Section C (12 weeks in the container).

Table 1. Compost Maturity Tests Conducted on Compost From Forced Air Container and Subsequent Curing Areas

	Compost Treatment			Compost Maturity Test			
Treatment Section	Duration in Forced Air Container (weeks)	Duration in Curing Area (weeks)	Total Compost Age (weeks)	Temperature Monitoring (continuous)	Solvita Maturity Test	Plant Germination and Dry Weight	Qualitative Observations
Section C	6	0	0	✓	✓	✓	✓
		3	9	✓	✓		✓
		6	12	✓	✓		✓
		9	15	✓	✓		✓
		12	18	✓	✓		✓
Section B	9	0	9	✓	✓	✓	✓
		3	12	✓	✓		✓
		6	15	✓	✓		✓
		9	18	✓	✓		✓
Section A	12	NA	12	✓	✓	✓	✓[a]
	15	NA	15	✓	✓		✓[a]
	18	NA	18	✓	✓		✓[a]

[a] Qualitative observations of Section A were limited because compost remained in the container and thus could not be as thoroughly evaluated as Sections B and C.

Temperature Monitoring

Temperature data loggers in each experimental section recorded the temperature every hour. A data logger was also placed several feet from the forced air system to record ambient temperatures. When material from Sections B and C was removed and placed in curing areas, the data loggers were placed in the center of each pile to continue recording hourly temperatures.

Temperatures were also analyzed to determine whether and when they met the federal time and temperature requirements to ensure significant reduction of pathogens. The U.S. EPA biosolids rule stipulates that compost temperature (for windrow and vessel compost methods) must exceed 104° F for 5 days and exceed 131° F for 4 hours (U.S. EPA, 2003) to reduce pathogens significantly.

Solvita Compost Maturity Test

Samples for the Solvita maturity test were collected for each of the treatments listed in Table 1. During each 3-week sample collection event (Table 1), nine point samples were collected from compost in the container sections and in the curing areas. Compost was sampled in accordance with Method B of the USCC Seal of Testing Assurance (STA) Program (USCC, 2010). For a single sample collection event, three horizontally dispersed point samples were collected (using a shovel and gloved hands) from each of three depths in the pile (the upper one-third, middle, and lower one-third of profile height). These nine samples (i.e., approximately 3 gal of compost) were thoroughly mixed, placed in 1-gal sealable plastic bags, and transferred in a cooler to the laboratory. Compost was passed through a 3/8-in sieve (in accordance with the Solvita maturity test methods) prior to analysis. Two Solvita maturity tests were conducted on compost from each sample collection event.

Plant Germination and Dry Weight Tests

Compost samples collected for the Solvita maturity tests were also used for plant growth tests. Radish seeds (Easter egg variety, *Raphanus sativus)* were used because of their rapid germination and growth (University of Florida, 2011). Fifty planting containers, each consisting of a nonporous 4 cm by 4 cm by 6 cm plastic cell, were used as the experimental seeds and the control seeds. Experimental seeds were grown with a 2:1 ratio by weight of commercial potting soil to compost; each seed in the experimental group was centered on 15 g of soil and covered with 7.5 g of compost. Each seed in the control group was centered on 15 g of soil and covered with another 7.5 g of soil.

Each experimental group (n = 50) was paired with a control group (n = 50); groups were placed side by side beneath high-intensity fluorescent grow lights and received 8 hours of light per day. Seeds were watered (5 ml) from the surface once per week. Tests were carried out in a controlled temperature laboratory with temperatures at 71.5° F (22° C), an optimum temperature for germination (Deno, 1993).

The number of seeds that germinated was documented each weekday. Each assay lasted 21 days, at the end of which the plants were harvested to determine dry weight and the final germination index, or relative seed germination. The germination index was applied to assess the percentage of experimental seeds that germinated relative to the control seeds and was calculated as follows:

$$\text{Germination index (\%)} = \frac{\text{Number of seeds that germinated in sample}}{\text{Number of seeds that germinated in control}} \times 100$$

To determine dry weight, seedlings were removed from the containers, rinsed to remove soil, and placed in a 200° F oven for 2 hours. Dried seedlings were weighed individually. A *t*-test was conducted to compare the dry weight of seedlings grown with compost to those grown with soil.

Qualitative Observations

Visual and odor evaluations provide important information about the properties of the compost (Itavaara et al., 2010). Compost was observed during its transfer (Sections B and C only) from the forced air containers to curing areas and each subsequent 3-week testing period (Table 1). The compost was evaluated for odor and inspected for dryness, presence of bones, and completeness of tissue degradation.

Overall Assessment of Compost Maturity: Forced Air System

Because compost maturity is best assessed by measuring more than one compost characteristic (USCC, 2010; Warman, 1999), the results of the quantitative tests (i.e., temperature, Solvita maturity, and plant tests) and the findings from the qualitative observations of compost from the forced air system were evaluated collectively. This allowed the researchers to provide an overall assessment of compost maturity under the varying treatments. Comparing results also provided an indication of whether some tests were more conservative than others as indicators of maturity.

Compost From Rotary Drum

Overview

A rotary drum at VDOT's Fishersville AHQ (Augusta County) was used in this part of the study (Figure 5). The 33-ft-long drum has a capacity of 300 to 400 lb per day (including the carbon source and the mortality). It has been operational since October 2013.

Figure 5. Rotary Drum at VDOT's Fishersville Area Headquarters, Augusta County

Mortalities were loaded into the drum with pine wood shavings in a 1:1 to 1:1.5 ratio by volume. According to the representative of the rotary drum vendor, the carbon source should be as dry as possible; the use of freshly processed or "green" woodchips is not recommended because of their higher moisture content (B. Irwin, personal communication). The primary VDOT operator provided the researchers with the date and number of mortalities loaded. The drum rotated once per day, and compost emerged from the end of the drum approximately 2 weeks after the loading event. Similar to compost generated from the forced air system, compost that emerges from the rotary drum is stored onsite in curing areas before ultimately being removed from the AHQ.

Compost Maturity Tests

In order to determine the time required for rotary drum compost to mature, temperature monitoring was conducted continuously and the Solvita maturity test and qualitative observations were conducted at 3-week intervals. Solvita maturity tests and qualitative observations were conducted on compost that (1) newly emerged from the rotary drum, and (2) emerged from the drum and was subsequently transferred to a curing area onsite (Table 2). A value of "0" in Table 2 indicates that the material collected for sampling had newly emerged from the drum and had not been subsequently piled in a curing area. Each sample collection event was preceded by a minimum loading rate of eight deer mortalities over the course of 2 weeks.

Monitoring of internal drum temperatures and temperatures of compost in the curing area was conducted over the course of 297 days (10 months) with the use of three instruments: (1) an internal temperature sensor (built into the drum) with an external display; (2) a 36-in Reotemp compost probe that can be inserted into the compost material through the loading door of the drum; and (3) a temperature data logger (set to record temperatures at 1-hour intervals) placed inside the drum and allowed to rotate freely with the compost material. Internal drum temperature was not used as a criterion for finished compost but rather to determine whether pathogen reduction requirements were met. The primary operator provided the researchers with temperature readings from the internal sensor and the compost probe and placed the data logger back in the drum each time it emerged from the end. Once the compost emerged from the drum, it was transferred to one of two curing areas (constructed 8 weeks apart). A data logger was inserted in the center of each pile to continue recording temperatures. Temperature data of compost in the curing area were analyzed to determine compost maturity and whether pathogen reduction thresholds were achieved.

Table 2. Compost Maturity Tests on Compost Generated From Rotary Drum and Compost Subsequently Transferred to Curing Area

Duration of Compost in Curing Area After Emerging From Drum	Maturity Test			
	Temperature Monitoring (Continuous)	Solvita Maturity Test	Plant Germination and Dry Weight	Qualitative Observations
0 (newly emerged from drum)	✓	✓	✓	✓
1 week	✓	✓		✓
3 weeks	✓	✓		✓
6 weeks	✓	✓	✓	✓
9 weeks	✓	✓	✓	✓

To collect samples of compost for the Solvita maturity and plant tests, five sample collection events were conducted (at 1-month intervals) on compost that emerged from the end of the drum during a rotation. For each sample collection event, compost emerging from the drum was allowed to fall into a 1-gal sealable bag over the course of 10 minutes. Samples were also collected at 3-week intervals (Table 2) from the curing area using the same nine point sample collection method described for the forced air system (USCC, 2001). Approximately 3 gal of compost were collected for each sample collection event, and samples were thoroughly mixed before testing. Two Solvita maturity tests were conducted on each sample.

Plant tests and qualitative observations were conducted at the sampling intervals listed in Table 2. Test methods were the same as those described for the forced air system.

Overall Assessment of Compost Maturity: Rotary Drum

The results of all compost maturity tests on compost from the rotary drum were evaluated collectively. This allowed for a comprehensive determination of the maturity of the compost that emerged from the drum and compost that was subsequently transferred to a curing area.

Evaluation of Suitability of Finished Compost for Application

Compost Characterization

Because the application of compost can impact biological, chemical, and physical properties of the soil (Gallardo-Lara and Nogales, 1987), it is important to characterize the properties of finished compost prior to use. Mature compost generated from the forced air system and the rotary drum was tested for a variety of properties in order to assess its suitability for application.

VDOT compost generated from the forced air system and the rotary drum that had reached maturation (according to the maturity tests described in this study) was sampled and tested in accordance with the USCC's STA Program (USCC, 2010). Samples were shipped overnight to an STA-approved testing laboratory in accordance with the procedure specified by the laboratory. Samples were analyzed for pH, carbon to nitrogen (C/N) ratio, soluble salt concentration, moisture content, organic matter content, respirometry (carbon dioxide evolution rate), physical contaminants, and particle size. Results were compared with AASHTO specifications (AASHTO, 2014a, b) and specifications in the report funded by the U.S. EPA (CCREF and USCC, 2008).

Demonstration Project

A project was conducted to demonstrate a beneficial use of finished compost at a VDOT facility. Application of finished compost also allowed a determination of whether the compost had processing requirements, specifically whether the quantity of remaining bones warranted their separation from the compost prior to use. Options to screen bones from compost were also investigated.

A steep eroding slope directly behind the forced air system at VDOT's Bethel AHQ was chosen as the demonstration site. The slope was predominantly bare of vegetation, and its continued erosion was a concern to the AHQ staff. Two plots, each approximately 20 ft by 20 ft, were delineated, and grass seed was spread over the existing dirt on each plot. One plot was left bare, and the other plot was covered with a compost blanket (i.e., a 2-in layer of loosely applied mature compost generated from the forced air system). The plots were photographed to provide a simple visual comparison of the effect of the compost blanket on grass establishment.

RESULTS AND DISCUSSION

Compost From Forced Air System at VDOT's Bethel AHQ

Compost Maturity Test Results

Temperature

Figure 6 illustrates the average daily temperatures recorded by data loggers in compost Sections A, B, and C. Temperatures reached a maximum of 172º F, 167º F, and 175º F in Sections A, B, and C, respectively. Although temperatures above 130º F are ideal for quickly destroying pathogens (Haug, 1993), the decomposition rate of organic matter decreases at temperatures above 158º F (Miyatake and Iwabuchi, 2005) and burning of the material becomes a risk. Temperatures that exceed 158º F can be reduced by watering the composting material more frequently with leachate pumped from the collection tank (K. Warren, personal communication).

The transfer of the compost from the forced air containers to curing areas at 6 weeks and 9 weeks (Sections C and B, respectively) initiated a steep drop in temperature quickly followed by a rapid increase. The temperatures of these sections then steadily declined at a faster rate than those of the compost that remained in the container (Section A). The mixing of material that occurs during removal of the compost from the container into a curing area likely increased the degradation activity by providing an additional supply of oxygen to the aerobic microbes (Itavaara et al., 2010), thereby leading to maturity faster than compost that remained in the container.

As mentioned previously, a national temperature standard for determining compost maturity does not exist in the United States; however, the VSWMR (9 VAC 20-81-340) stipulate that temperature decline to "near ambient conditions" is one of the accepted test methods for determining compost maturity. Canada's national composting standards provide a specific value; one of their accepted determinants of compost maturity is that the "temperature rise of compost above ambient is less than 8° C [14.4° F]" (CCME, 2005). Temperature analyses from a recent animal mortality compost study (Donaldson et al., 2012) determined a higher upper limit, or threshold, above ambient when using course woody material (i.e., woodchips) as the carbon source.

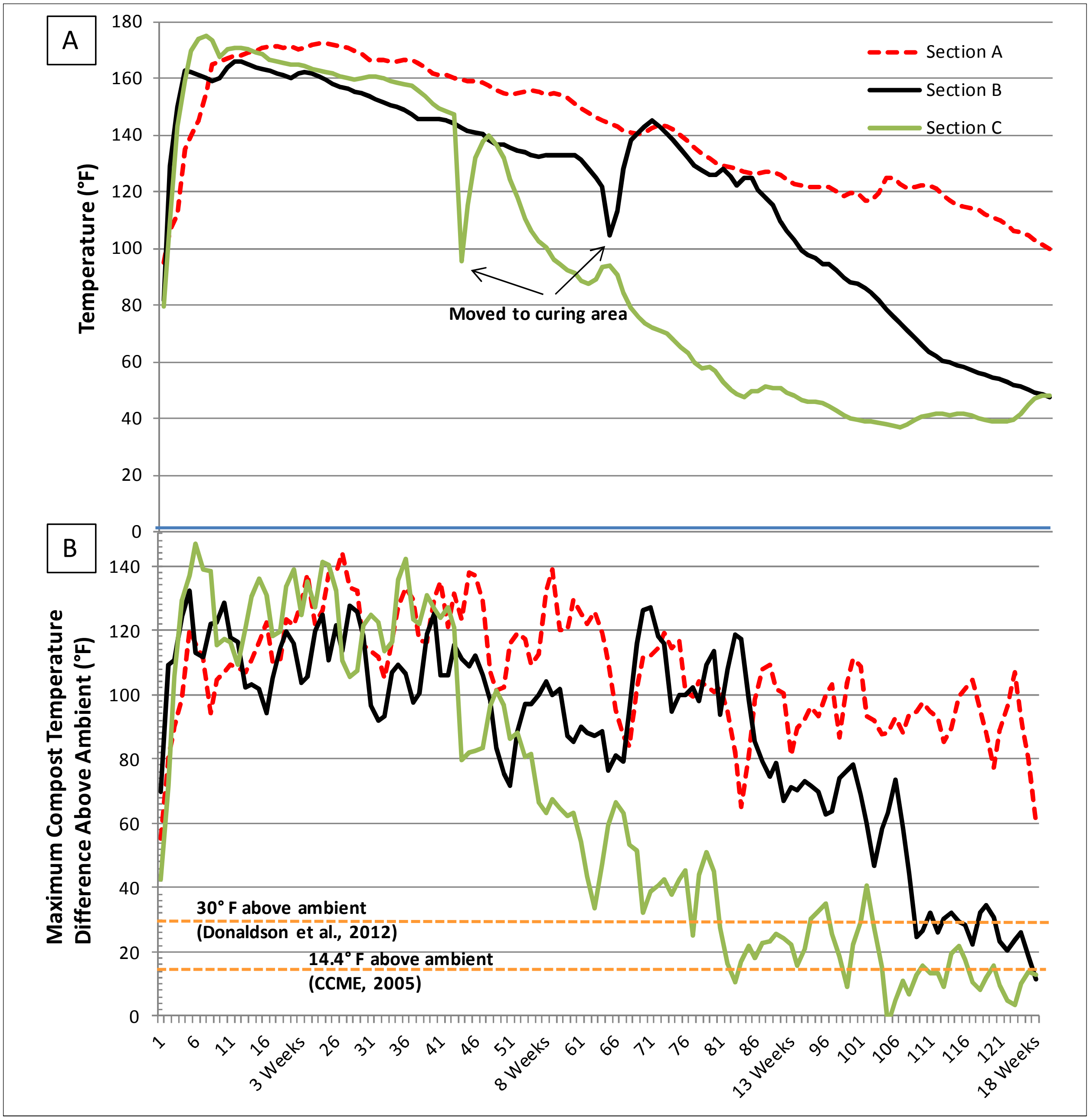


Figure 6. A: Daily Average Temperatures of Compost From Section A (which remained in forced air container); Section B (transferred from container to curing area at 9 weeks); and Section C (transferred from container to curing area at 6 weeks). B: Daily Maximum Temperature Difference Above Ambient. Delineating thresholds above ambient were determined by Donaldson et al. (2012) and required by the Canadian Council of Ministers of the Environment (CCME) (2005).

The degradability and associated heat release of carbon sources common to composting can vary widely; woody material degrades slowly and can continue to produce heat over long periods (Haug, 1993). The animal mortality study, which included a comparison of temperatures of compost windrows comprising woodchips and deer mortality and temperatures of a control pile comprising only woodchips, found that the temperature of the woodchips that served as the control pile (containing no deer) remained higher than ambient temperatures over the course of the 12-month monitoring period. The woodchip pile produced temperatures up to 65° F above ambient, with the daily maximum difference between ambient temperatures and the temperatures of the woodchip pile averaging 30° F (Donaldson et al., 2012). For compost comprising woody material as the carbon source, the authors determined that using this average threshold of 30° F above ambient was a more suitable means for examining compost maturity than comparing compost temperatures with ambient temperatures.

An examination of the compost temperatures in the forced air treatments in the context of the findings of Donaldson et al. (2012) and the CCME (2005) threshold of 14.4° F showed that the compost temperature in Section C (compost that was transferred to a curing area at 6 weeks) was the first to remain below the 30° F above ambient threshold after Day 102 (14.5 weeks) and below the 14.4° F threshold 3 days later. In other words, compost that was removed from the forced air container after 6 weeks met these temperature criteria after approximately 8.5 weeks in a curing area. The compost temperature in Section B first remained below the 30° F threshold after Day 120 (approximately 17 weeks, or 9 weeks in the forced air container followed by nearly 8.5 weeks in a curing area) and then fell below the 14.4° F threshold 5 days later. The temperatures of the compost that remained in the container (Section A) did not drop below 30° F over the duration of the 18-week monitoring period (Figure 6B). It is possible that the high temperatures at the end of the monitoring period in Section A were not necessarily an indication of unfinished compost but rather were a result of the containers preventing heat loss more so than compost in the curing area.

With regard to pathogen destruction, the temperature results verified what had been determined in a previous evaluation of this forced air system (Donaldson and White, 2013). Temperatures in each of the three compost treatments (Sections A, B, and C) met (and even exceeded) the requirements for pathogen reduction in the U.S. EPA's biosolids rule (exceed 104° F for 5 days and exceed 131° F for 4 hours) (U.S. EPA, 2003) within 5 days after the sections were constructed.

Solvita Compost Maturity

Table 3 lists the Solvita maturity test results. According to these results, compost from Section C matured steadily once it was transferred to a curing area at 6 weeks. This compost met the VSWMR criteria, which specify that compost with a Solvita maturity index of 6 or higher is stable and therefore suitable for use (Virginia Register of Regulations, 2011) after 6 weeks in the forced air container followed by an additional 6 to 9 weeks in a curing area. Compost from Section B had an index of 6 or higher immediately upon removal of the compost from the container at 9 weeks. For Section A compost (which was first tested at 12 weeks), one of the two samples had an index of 5 and the other had an index of 6. Subsequent samples had an index of 6 or higher.

Table 3. Solvita Compost Maturity Test Results for Compost Generated in Forced Air System and Subsequently Transferred to Curing Area

Section	Compost Treatment			Solvita Maturity Test Results	
	Duration in Forced Air Container (weeks)	Duration in Curing Area (weeks)	Total Compost Age (weeks)	Solvita Maturity Index[a]	Description
Section C	9 weeks	0	6	4-5	Compost is in moderately active stage of decomposition
		3	9	5	Compost is moving past the active phase of decomposition and is ready for curing
		6	12	5-6	Compost is curing
		9	15	6	Compost is mature and suitable for use
		12	18	6- 7	Compost is well matured and suitable for use
Section B	9 weeks	0	9	6-7	Compost is well matured and suitable for use
		3	12	6-7	Compost is well matured and suitable for use
		6	15	6	Compost is mature and suitable for use
		9	18	6-7	Compost is well matured and suitable for use
Section A	12 weeks	NA	12	5-6	Compost is curing
	15 weeks	NA	15	6	Compost is mature and suitable for use
	18 weeks	NA	18	6-7	Compost is well matured and suitable for use

[a] Ranges from 1 to 8 in whole numbers (Woods End Laboratories, Inc., 2013). Reported indices represent the average of two Solvita maturity tests conducted for each sample.

Plant Germination and Dry Weight

Figure 7 illustrates the germination index of seeds grown with compost from Sections A, B, and C compared to seeds grown with soil. The higher the index, the greater the germination rate of seeds covered with compost relative to those covered with soil. A germination index of 100% indicates that the cumulative number of seeds that germinated was the same for seeds grown with compost as for those grown with soil. One of the tests for compost maturity in Canada's compost standards concerns germination: "the germination of cress and radish seeds in compost shall be greater than a value corresponding to at least 90% of the germination rate of the control sample" (i.e., a germination index of 90%) (CCME, 2005). In the United States, the AASHTO specifications (Alexander, 2003) for compost used in roadside applications are more lenient; they specify that the germination of seeds in compost should be at least 80% of the germination rate of the control sample (i.e., a germination index of 80%).

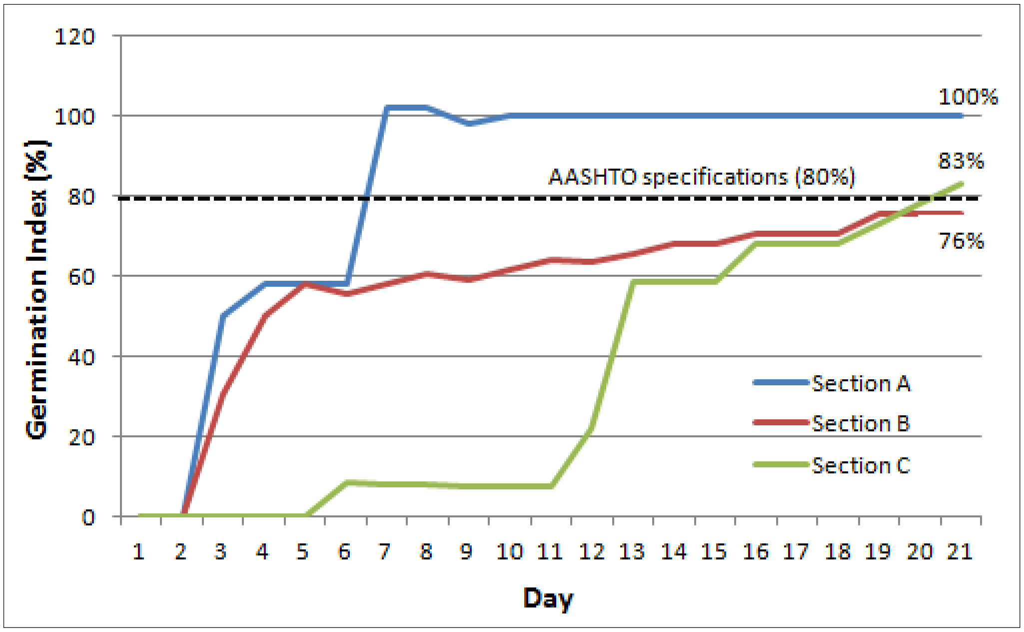


Figure 7. Daily Germination Index of Seeds Grown With Compost Relative to Those Grown With Soil. Plants were grown with compost removed from the forced air container at 12 weeks of age (Section A); 9 weeks of age (Section B); and 6 weeks of age (Section C). AASHTO specifications = as cited in Alexander (2003).

Seedlings grown with compost from Section A (12 weeks old) germinated the fastest and had the highest germination index (attaining over 100% germination relative to the control by Day 7). Only seedlings grown with compost from Section B (9 weeks old), with a 76% germination index fell just below the 80% germination index specified by AASHTO (as cited in Alexander, 2003). The longest delays of germination occurred with plants grown with the youngest compost (Section C, 6 weeks old), although the germination index had increased to 83% by the end of the testing period (Figure 7).

Immature compost can contain phytotoxic organic compounds (such as high ammonium concentrations) that can inhibit germination and growth (Warman, 1999); however, Itavaaar et al. (2010) and Warman (1999) found that the immature composts do not always inhibit germination. Germination delays for seeds grown with the compost may have been a result of initial phytotoxicity (Warman, 1999), often caused by a high concentration of ammonium (Itavaara et al., 2010). Delays may also be explained by an initial unavailability of nutrients to the plants, since microbes in unfinished compost use the compost nutrients to decompose the organic matter (University of Florida, 2011). The plant monitoring period of 21 days may have allowed sufficient maturation of the compost to promote germination.

Table 4 lists the mean dry weights of seedlings grown with compost and those grown with commercial potting soil. A *t*-test indicated no statistically reliable difference between the mean dry weight of seedlings from the control group grown with only soil and those grown with 6-week-old compost from Section C ($p = 0.111$, $\alpha = 0.05$). The mean dry weight of seedlings grown with 9-week-old compost from Section B was significantly greater than that of seedlings grown with soil ($p = 0.000$, $\alpha = 0.05$). This was an interesting finding, considering that 76% of the seeds planted with compost germinated relative to those planted with soil (Figure 7). The seedlings grown with 9-week-old compost were also larger in appearance, although length was not measured (Figure 8). The mean dry weight of seedlings grown with 12-week-old compost from Section A was also significantly greater than that of those grown with soil ($p = 0.000$, $\alpha = 0.05$). The 9- and 12-week-old compost likely acted as a nutrient source (similar to fertilizer), improving soil properties and promoting plant growth (Warman, 1999).

Table 4. Mean Dry Weights of Seedlings Grown in Compost Generated From Forced Air System (Experimental) and Seedlings Grown Only in Potting Soil (Control)

Experimental/Control Pair		Experimental/Control Pair		Experimental/Control Pair	
6 weeks (Section C)	**Potting Soil**	**9 weeks (Section B)**	**Potting Soil**	**12 weeks (Section A)**	**Potting Soil**
14.0 ± 3.0	16.4 ± 8.0	51.3 ± 6.8*	16.4 ± 8.2	43.2 ± 14.2*	29.6 ± 11.8

Note: Each experimental group (compost) was paired with a control (potting soil). Fifty seeds were planted in each test group.
*Significant difference between seedlings grown with compost and those grown with potting soil.

Figure 8. Seedlings Grown With Section B 9-Week-Old Compost *(left)* and Potting Soil *(right)*

Qualitative Observations

The appearance of the compost generated from the forced air system was similar to that of the coarse woody matter (sawdust) that served as the carbon source (Figure 9). For each testing period, the compost was moist (but not wet) and free of non-compostable material with the exception of occasional small stones from the crushed stone surface on which the compost was piled. Bones, which are common even in finished animal mortality compost (Bonhotal et al., 2007), were often present (Table 5).

A strong ammonia odor was noticeable upon transfer of the compost from Section C to a curing area, indicative of the immaturity of the compost. Compost can have a very low C/N ratio during the active phase of composting when proteins are degrading, which may cause high ammonia emissions (Itavaara et al., 2010). As compost from Sections B and C aged in curing areas, unpleasant odors decreased and bone degradation was evident. For Section A compost that remained in the container, tissue and bone degradation was more difficult to assess than for compost from the other sections that was transferred to curing areas.

Figure 9. Finished Compost From Forced Air System (9 weeks of age)

Table 5. Qualitative Observations of Compost Generated From Forced Air System

Section	**Compost Treatment: Duration in Forced Air Container (weeks)**	**Duration in Curing Area (weeks)**	**Total Compost Age (weeks)**	**Odor and Presence of Bones[a]**
Section C	6	0	6	Strong ammonia odor, numerous large bones and incomplete tissue degradation
		3	9	Ammonia odor, numerous bones
		6	12	Mild odor, small bones
		9	15	No odor, few bones
		12	18	No odor, few bones
Section B	9	0	9	Mild odor, bones
		3	12	Mild odor, bones
		6	15	No odor, few bones
		9	18	No odor, few bones
Section A	12	NA	12	No odor[b]
	15	NA	15	No odor[b]
	18	NA	18	No odor[b]

[a] Only unpleasant odors are noted.
[b] Because Section A compost remained in the container and thus was difficult to assess thoroughly, observations of Section A compost were limited to odor.

Overall Assessment of Compost Maturity: Forced Air System

Figure 10 lists the results of the quantitative tests of each of the compost treatments (Sections A, B, and C) generated from the forced air system. Evaluating these test results collectively allowed for a determination of the point at which compost in each treatment reached maturity.

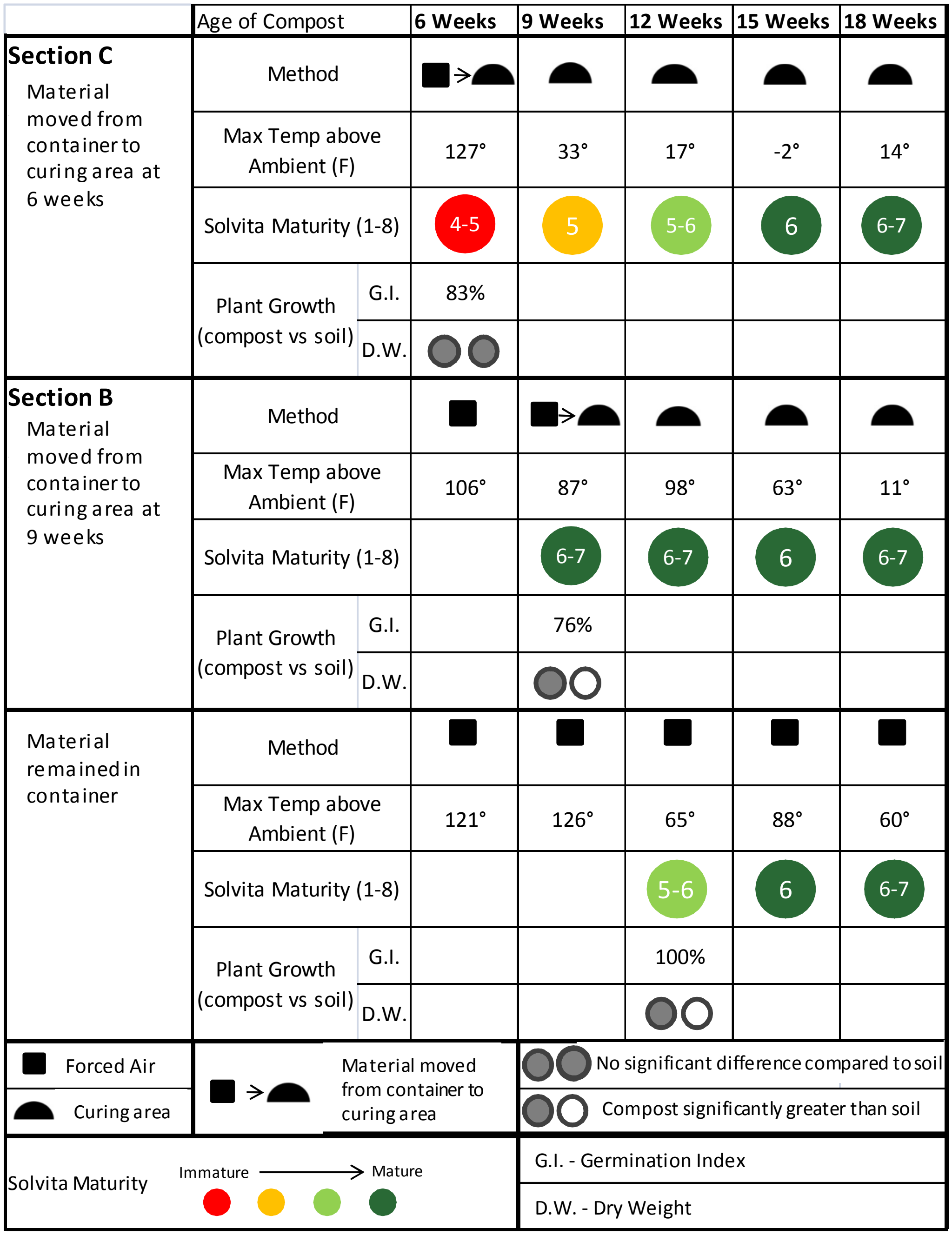


Figure 10. Results of Compost Tests Conducted on Treatments A, B, and C. Solvita maturity index results are the average of two tests.

The 6-week-old compost from Section C was in the active composting phase, as indicated by its high temperature (up to 127° F above ambient), low Solvita maturity index (4-5), delayed seed germination, and incomplete tissue degradation. As the compost aged in a curing area, the Solvita maturity index increased as temperatures above ambient decreased (both indicative of compost maturation) over the course of subsequent 3-week test intervals. The Solvita maturity test results indicated compost maturity between ages 12 and 15 weeks (i.e., 6 to 9 weeks after curing in a curing area). This is consistent with low odor and a minimal number of small bones after 12 weeks (Table 5) and the temperature drop below the 30° F above ambient thresholds at approximately14.5 weeks (or 6 weeks in the container and 8.5 weeks in a curing area).

For Sections A and B, Solvita maturity and plant growth test results indicated that compost was mature at earlier testing periods than was denoted by the temperature decline. For these sections, qualitative observations (i.e., no to low odor, few remaining bones; Table 5) were more closely correlated with the Solvita maturity and plant test results than with the high temperature. Temperatures of compost from Section B were still well above ambient (by a maximum of 87° F) when it was transferred from the container at 9 weeks to a curing area, indicating that the compost was immature, but the Solvita maturity index (6-7) and the plant weights (significantly greater than the control) suggested mature compost. Section B temperatures did not fall below the 30° F above ambient threshold until 17.5 weeks (i.e., 8.5 weeks after curing in a curing area, Figure 6B), but the Solvita maturity index indicated mature compost at earlier testing periods (9, 12, and 15 weeks).

For Section A, although the Solvita maturity test results indicated that compost was mature by week 15, temperatures did not decline below 30° F throughout the 18-week monitoring period. As mentioned previously, it is possible that the high temperatures of the compost in the containers were in part attributable to a lesser potential for heat loss from the four-walled containers rather than being indicative of incomplete maturation. Regardless of its maturity, transferring compost from the containers to cool in a curing area would be more prudent than applying the compost when temperatures were still high.

It was not until compost was transferred to a curing area for a minimum of 8.5 weeks that all tests conducted indicated finished compost. Temperature was the most conservative indicator. Supplementing temperature monitoring with qualitative observations is easy and is a practical monitoring method for an AHQ operator. Transferring compost as young as 6 weeks to a curing area to cure for a minimum of 8.5 weeks and verifying that the temperature is no greater than 30° F above ambient is expected to ensure that compost is ready for application.

Compost From Rotary Drum at VDOT's Fishersville AHQ

According to the log entries maintained by the primary operator, 101 deer and 39 other species (i.e., raccoon, opossum, cat, dog, fox, groundhog, and calf) were loaded into the drum from October through July at VDOT's Fishersville AHQ (Table 6). A single loading event ranged from one to three deer or an equivalent or smaller volume of smaller species. Because deer mortalities are typically high in November and early December, the low deer mortality volumes recorded those months (Table 6) suggest that some loading events throughout the monitoring period were not documented because of other work demands on the operator.

Table 6. Animal Mortalities Recorded in Log Book for Rotary Drum

Month	Deer	Other	Total
October	19	6	25
November	5	2	7
December	3	0	3
January	10	0	10
February	6	14	20
March	17	2	19
April	10	4	14
May	8	8	16
June	6	0	6
July	17	3	20
Total	101	39	140

Compost Maturity Test Results

Temperature

The temperature of the material composting inside the rotary drum was difficult to assess accurately. Although the operator was responsible for documenting temperature readings from the internal sensor (located near the center of the drum) and from the compost probe (inserted by the operator through the loading door near the front end of the drum), this task was difficult to conduct on a daily basis because of the operator's other AHQ responsibilities. Temperature data were provided to the researchers on 98 days of the 297-day monitoring period (33%). Further, temperatures were recorded at various times of the day relative to the daily drum rotation. This is important because compost temperatures drop steeply after each rotation of the drum and take hours to increase to the day's maximum temperature (B. Irwin, personal communication). The optimum time of day to gauge temperature is just prior to drum rotation, but this was rarely possible given the other work demands on the AHQ operators. Although the data logger that rotated freely within the drum recorded hourly temperatures (which were uploaded to a computer each time the logger emerged from the drum), there were no means of ensuring that the hottest area of compost was being recorded.

Internal drum temperatures recorded by the three instruments were often inconsistent with one another, likely a result of the different locations of the instruments recording temperature. Temperatures were recorded by all three instruments on the same day on 35 occasions. Of these, the temperatures recorded by the data logger were up to 97° F higher than those recorded by the internal drum sensor, with an average difference of 40° F. Temperatures recorded by the data logger were not consistently the highest among the three instruments, however; 43% of the highest temperatures were recorded by the probe. The highest temperatures recorded by *any* instrument on these 35 occasions ranged from 118° F to 162° F and averaged 138° F.

These inconsistencies among temperature readings indicate that the highest temperature of the compost in the drum was not consistently recorded throughout the monitoring period. Despite this, 71% of the highest daily temperature readings (recorded by any of the three instruments) were greater than 104° F and with few exceptions remained above 104° F for at least the 5 consecutive day regulatory threshold (U.S. EPA, 2003). It could not be determined whether the remaining 29% of readings represented the hottest portion of compost in the drum. Temperature readings became reliable, however, once the material that emerged from the end of the drum was transferred to a curing area.

Figure 11 illustrates temperature results over the course of two monitoring events (April through July and June through September). Each event comprises 3 weeks of temperature readings from the data logger inside the drum followed by 3 months of readings from compost in the curing area.

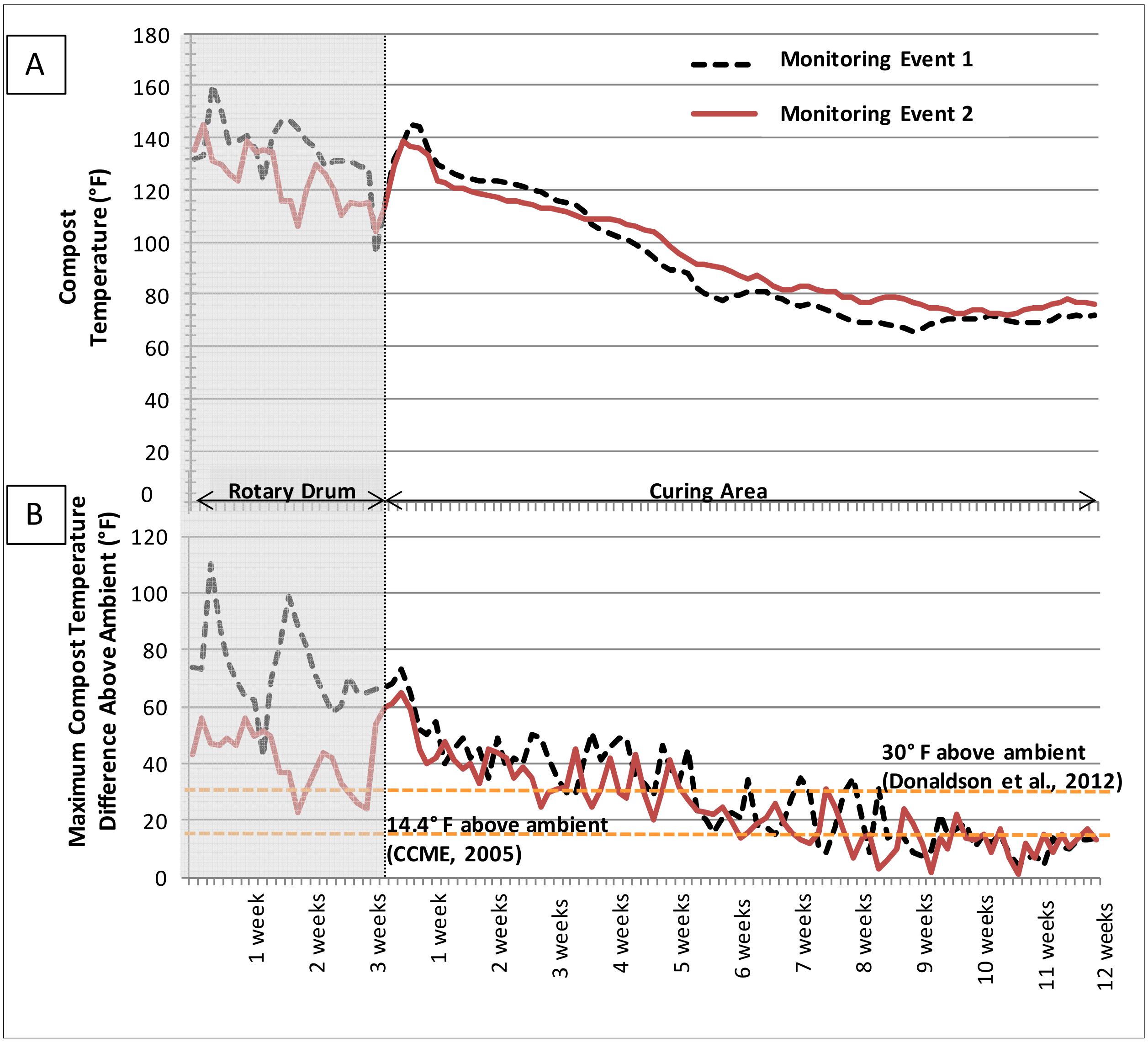


Figure 11. Temperature Information Over Course of Two Monitoring Events (April through July and June through September, 2014). Each event comprised 3 weeks of temperatures recorded within the rotary drum (*shaded area*) followed by 12 weeks in a curing area. A: Highest daily temperatures recorded within the rotary drum followed by daily average temperatures of compost in the curing area. B: Daily maximum temperature difference above ambient. The delineating thresholds above ambient were determined by Donaldson et al. (2012).

Because a temperature decline to near ambient conditions is a common method for determining compost maturity (Virginia Register of Regulations, 2011), Figure 11B illustrates the compost temperature difference above ambient temperatures. The temperature discrepancies in the rotary drum between Monitoring Events 1 and 2 (Figure 11B) were largely a result of the different ambient temperatures between April (when Monitoring Event 1 began) and June (when Monitoring Event 2 began).

Because of the inconsistent temperature readings of compost inside the drum, it was difficult to evaluate temperature conditions for pathogen reduction. Transferring compost generated from the drum to a curing area not only ensured that compost had time to mature fully but also provided a means to assess temperature reliably and thereby ensure that pathogen requirements were attained. Once the compost generated from the drum was transferred to a curing area (Day 21), an initial drop in temperature was quickly followed by a steep rise (Figure 11A). Compost temperatures increased to a maximum of 145° F and 142° F and exceeded the federal pathogen reduction requirement (U.S. EPA, 2003) within 3 days following the transfer of the compost to the curing area. Following this period of sustained high temperatures, temperatures steadily declined toward ambient temperatures (an indication of maturation) (Virginia Register of Regulations, 2011).

A comparison of the temperatures of compost in the curing area and the above ambient thresholds of 14.4° F (CCME, 2005) and 30° F (Donaldson et al., 2012) showed that the compost temperature recorded during Monitoring Event 1 remained below the 30° F above ambient threshold after 57 days (8 weeks) in a curing area and generally remained below the 14.4° F threshold 1 day later (Figure 11B). The compost temperature recorded during Monitoring Event 2 remained below the 30° F temperature threshold after 53 days (7.6 weeks) in a curing area and generally remained below the 14.4° F threshold 3 days later.

Solvita Compost Maturity

Table 7 lists the results of the Solvita maturity tests. The Solvita maturity index for three of the five samples of compost that emerged from the drum (Samples 1, 2, and 5 in Table 6) indicated the material was at the end of its active composting phase (index of 5). Because an index of 6 or higher indicates mature compost, this compost was not considered stable and suitable for use (Virginia Register of Regulations, 2011; Woods End Laboratories, Inc., 2013). Two of the samples of compost that emerged from the drum had a higher index (i.e., 6-7), indicative of mature compost.

The Solvita maturity tests indicated a gradual maturation of the compost as it cured in the curing area (Table 7). For compost that remained in the curing area a minimum of 3 weeks, the Solvita maturity index was 6 or higher.

Table 7. Solvita Compost Maturity Test Results for Compost Generated in Rotary Drum and Transferred to Curing Area

Compost Treatment		Solvita Compost Maturity Test Results	
Rotary Drum	**Duration in Curing Area (weeks)**	**Solvita Maturity Index[b]**	**Description**
	0 (newly emerged from drum)[a]	Sample 1: 5	Compost is moving past active phase of decomposition and is ready for curing
		Sample 2: 5	Compost is moving past active phase of decomposition and is ready for curing
		Sample 3: 6-7	Compost is well matured and suitable for use
		Sample 4: 6-7	Compost is well matured and suitable for use
		Sample 5: 5	Compost is moving past active phase of decomposition and is ready for curing
	1	5-6	Compost is curing
	3	6-7	Compost is well matured and suitable for use
	6	7	Compost is well matured and suitable for use
	9	7	Compost is well matured and suitable for use

[a] Samples of compost newly emerged from the drum were collected at 4-week intervals.
[b] Reported indices are the average of two Solvita maturity tests conducted for each sample.

Plant Germination and Dry Weight

Figure 12 shows the germination index of seeds grown with compost samples (of compost exiting the rotary drum and compost subsequently stored in a windrow for 6 and 9 weeks) compared to seeds grown with soil. A germination index greater than 100% indicates that the cumulative number of seeds that had germinated was greater for seeds grown with compost than for seeds grown with soil.

Seeds grown with compost that cured in a curing area for 6 and 9 weeks germinated quickly and had a high germination index (104% and 111%, respectively). The longest delays of germination occurred with the seeds grown with compost that emerged from the drum exit, although the germination index increased to 82% by the end of the testing period (meeting the 80% or higher requirement specified by AASHTO as cited in Alexander [2003]). Similar to the test results from compost generated from the forced air system, delays in germination may have been a result of initial phytotoxicity of the compost, indicating that the compost requires further curing (Warman, 1999).

Table 8 compares the mean dry weights of seedlings grown with compost of varying ages from the rotary drum to those grown with commercial potting soil. A *t*-test indicated no statistically reliable difference between the mean dry weight of seedlings from the control group grown with only soil and those grown with newly emerged compost from the drum ($p = 0.07$, $\alpha = 0.05$). The mean dry weights of seedlings grown with compost from the drum that subsequently cured for 6 weeks and 9 weeks in a curing area were significantly greater than those grown with soil ($p = 0.04$ and $p = 0.002$, $\alpha = 0.05$, respectively).

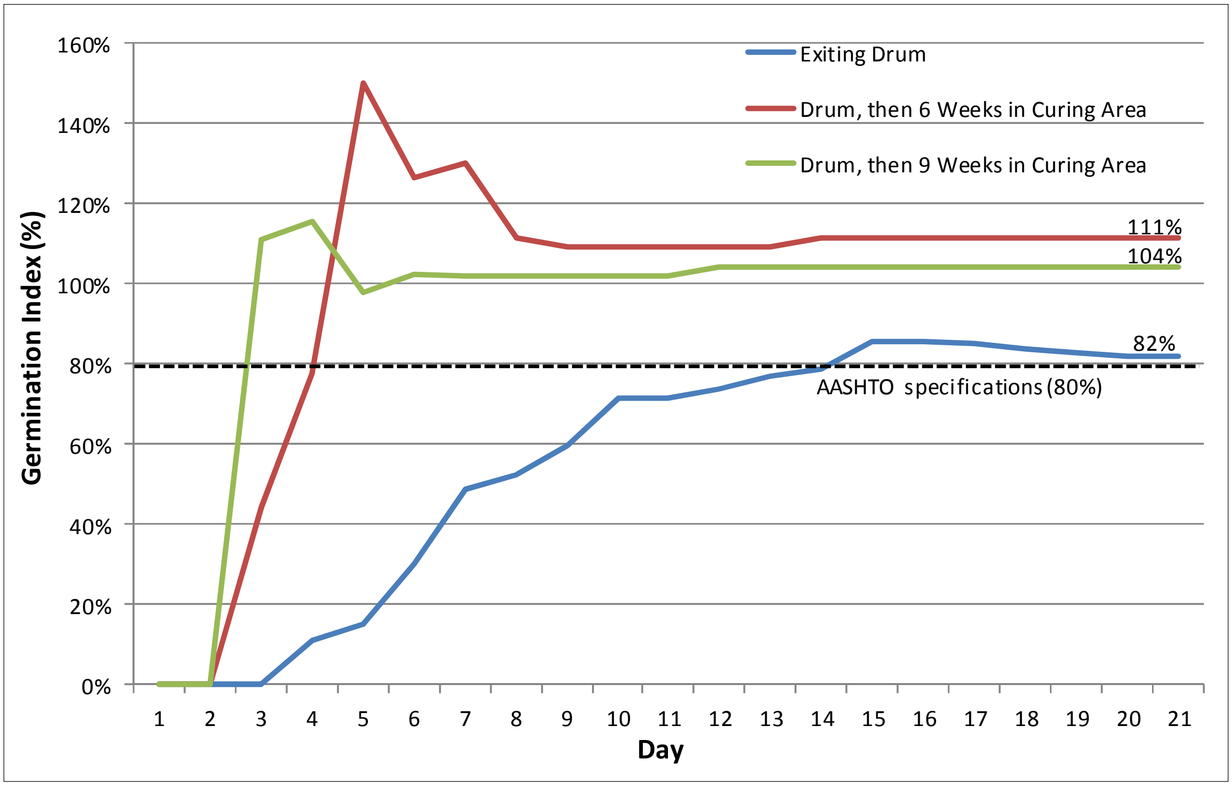


Figure 12. Daily Germination Index of Seeds Grown With Compost Relative to Those Grown With Soil. Seeds were grown with samples of compost exiting the rotary drum; samples of compost that were transferred from the drum exit and placed in a curing area for 6 weeks; and samples of compost transferred from the drum exit and placed in a curing area for 9 weeks. AASHTO specifications = as cited in Alexander (2003).

Table 8. Means and Standard Deviations of Dry Weight of Seedlings Grown in Compost From Rotary Drum (Experimental) and Seedlings Grown Only in Potting Soil (Control)

Experimental/Control Pair		Experimental/Control Pair		Experimental/Control Pair	
Compost Newly Emerged From Drum	Potting Soil	Compost in Curing Area (6 weeks)	Potting Soil	Compost in Curing Area (9 weeks)	Potting Soil
32.7 ± 17.9	43.1 ± 30.4	46.1 ± 25.3*	28.0 ± 9.1	57.8 ± 25.4*	43.5 ± 16.2

Note: Each experimental group (compost) was paired with a control (potting soil). Fifty seeds were planted in each test group.
*Significant difference between seedlings grown with compost and those grown with potting soil.

Qualitative Observations

The compost generated from the rotary drum contained numerous bones (12 in and smaller), but there was no visible animal tissue and the compost appeared similar to the sawdust that served as the cover material (Figure 13). A faint ammonia odor was evident on three of the five occasions that compost that exited the drum was sampled (Samples 1, 2, and 5 in Table 7), indicating that the compost was not fully mature (Itavaara et al., 2010). Once the compost was transferred to curing areas, the number of bones appeared to decrease as the compost finished curing. Each testing period, the compost felt sufficiently moist and was free of non-compostable material with the exception of occasional small stones from the crushed stone surface on which the compost was piled. Compost evaluations for odor and appearance are provided in Table 9.

Figure 13. Compost From Rotary Drum

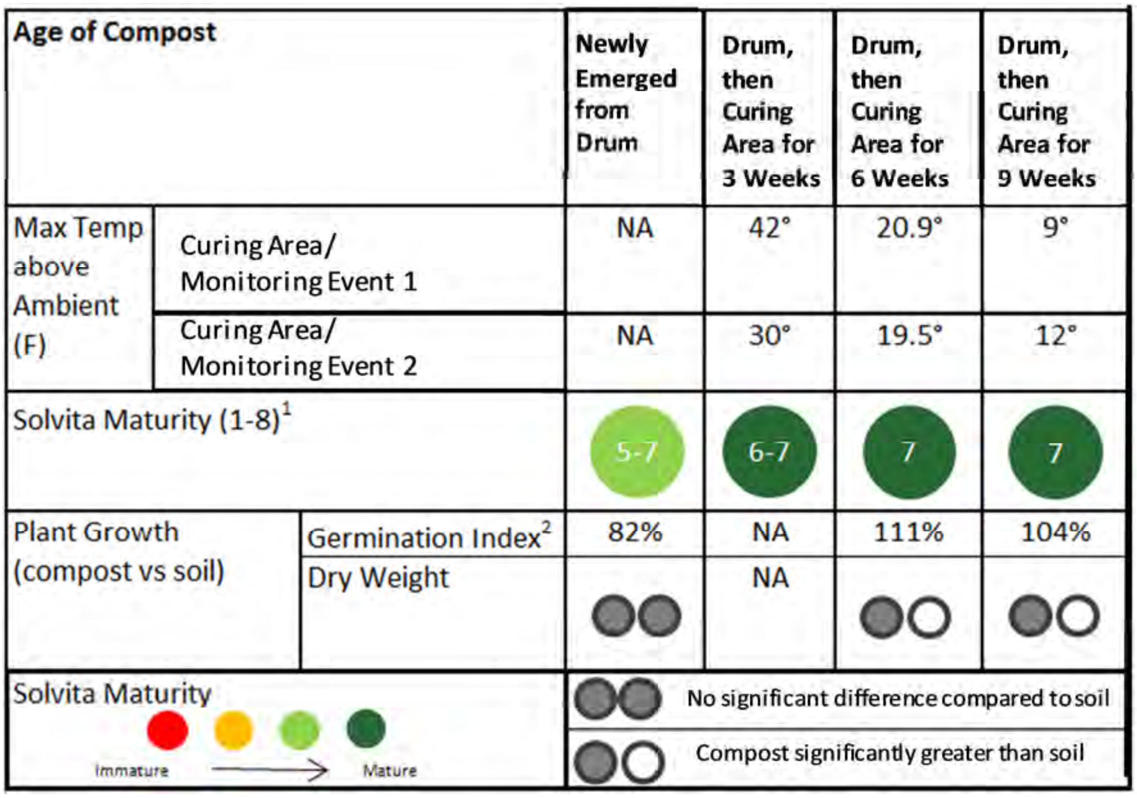
Table 9. Qualitative Observations of Compost Generated From Rotary Drum

Compost Treatment		Odor and Presence of Bones (only unpleasant odors noted)
Rotary Drum	**Duration in Curing Area (weeks)**	
	0 (newly emerged from drum)	Mild odor, with traces of ammonia odor during 3 of the 5 observations Numerous small bones but complete tissue degradation
	1	Mild odor, numerous bones
	3	Mild odor, several small bones
	6	No odor, few small bones
	9	No odor, few small bones

Overall Assessment of Compost Maturity: Rotary Drum

Figure 14 shows the results of the quantitative tests of each of the rotary drum compost treatments. With the exception of two of the five Solvita maturity tests, all results indicated that the compost generated from the rotary drum required further curing in a curing area. Similar to the findings for compost generated from the forced air system, seedlings grown with compost that was not fully mature (according to the other test results) took longer to germinate than plants grown with potting soil. Seeds grown with compost from the drum that subsequently cured for several weeks in a curing area grew into significantly larger plants (by weight) than those grown only with soil.

As with the forced air compost test results, temperature was the most conservative indicator of the maturity of compost generated from the rotary drum. Results from the Solvita maturity and plant tests suggested that compost in the curing area was mature a few weeks earlier than indicated by temperature. With the use of temperature as the primary indicator of maturity, compost generated from the drum reached maturity after 8 weeks in a curing area.



Age of Compost			Newly Emerged from Drum	Drum, then Curing Area for 3 Weeks	Drum, then Curing Area for 6 Weeks	Drum, then Curing Area for 9 Weeks
Max Temp above Ambient (F)	Curing Area/ Monitoring Event 1		NA	42°	20.9°	9°
	Curing Area/ Monitoring Event 2		NA	30°	19.5°	12°
Solvita Maturity (1-8)[1]			5-7	6-7	7	7
Plant Growth (compost vs soil)		Germination Index[2]	82%	NA	111%	104%
		Dry Weight	●●	NA	●○	●○
Solvita Maturity: Immature → Mature			●● No significant difference compared to soil			
			●○ Compost significantly greater than soil			

Figure 14. Compost Tests (temperature above ambient, Solvita maturity test, and plant growth test) Conducted on Treatments of Compost Generated From Rotary Drum. The Solvita maturity index results are the average of two tests.

Suitability of Finished Compost for Road Project Applications

Compost Characterization

AASHTO (2013a, b) and the report funded by the U.S. EPA (CCREF and USCC, 2008) provide similar specifications for using compost for transportation landscape applications such as sediment and erosion control. The AASHTO criteria for the use of compost for vegetation establishment are stricter than those for erosion control and slope stabilization (AASHTO, 2013b). Table 10 lists the specifications and the results of the characterization tests of compost generated from VDOT's forced air system and rotary drum. Compost from VDOT's forced air system met all U.S. EPA and AASHTO specifications. Compost from the rotary drum met U.S. EPA specifications but exceeded the upper limit of certain AASHTO specifications (as noted in Table 10). It is important to note that these specifications are provided only as guidelines transportation agencies can use if they choose to develop their own specifications.

Although the C/N ratio listed in Table 10 is not a variable listed in the U.S. EPA or AASHTO specifications, it is generally considered to be an important parameter for depicting the proper degradation of organic waste. A proper C/N ratio will result in a composting environment where microorganisms can flourish (Itavaara et al., 2010). The C/N ratio of composted material varies in part based on the C/N ratio of the carbon source. Woodchips, sawdust, and wood shavings can have a C/N ratio from 100:1 to 1,000:1 (Rynk et al., 1992). The C/N ratio of well-composted materials also varies widely, from 5:1 to 20:1 (Chanyasak and Kubota, 1981). In some regions, a product is not considered to be compost unless the C/N ratio is less than 25:1 (Woods End Laboratories, Inc., 2013). Because of the wide variations in acceptable ratios for compost, the C/N ratio cannot be used as an absolute indicator of compost maturity (Bonhotal et al., 2014, Chanyasak and Kubota, 1981; Woods End Laboratories, Inc., 2013).

Table 10. AASHTO and U.S. EPA Specifications for Using Compost for Erosion and Sediment Control and Results of Compost Analyses of Compost Generated From VDOT's Forced Air System and Rotary Drum

		Compost Specifications for Transportation Applications		VDOT Compost Characterization	
Variable Measured	**Unit**	**AASHTO (2013a, b)**	**U.S. EPA (CCREF and USCC, 2008)**	**Forced Air**	**Rotary Drum**
pH	(-logH+)	5-8.5 vegetated (NA unvegetated)	5-8.5	6.16	5.73
Carbon/nitrogen ratio	ratio	NA	NA	14.4:1	24.5:1
Soluble salt concentration	dS-m^(-1)	Max 5 (NA unvegetated)	Max 10	3.3	6.3[a]
Moisture content	%	30-60	30-60	59	39
Organic matter content	%	25-65 vegetated (25-100 unvegetated)	30-65	56.2	56.8
Carbon dioxide evolution rate	mg CO2-C per day	<8 (NA unvegetated)	NA	0.21	0.63
Physical contaminants (inerts)	%, dry weight basis	<1	NA	0	14.3[b]
Particle size (% passing)	%	3-in sieve: 100	NA	100	100
		1-in sieve: 90-100	NA	100	100
		¾-in sieve: 65-100	¾-in sieve: 98	100	100
		¼-in sieve: 0-75		73	90[c]

NA = not applicable; the specification is not provided in the document.
[a] Meets U.S. EPA specification and meets AASHTO specifications for unvegetated (but not vegetated) compost blanket and filter sock/berm.
[b] Meets U.S. EPA specification but does not meet AASHTO specifications. All physical contaminates (inerts) were small stones, likely from the crushed stone surface of the area headquarters lot.
[c] Meets U.S. EPA specification but does not meet AASHTO specifications.

Demonstration Project

At VDOT's Bethel AHQ demonstration site, the plot covered with a blanket of compost generated from the forced air system appeared to have a thicker cover of grass than the plot left bare (Figure 15). Similar to the findings of the plant growth tests, this project demonstrates the value of compost for vegetation establishment. In addition to providing an aesthetic benefit, compost serves the important functions of soil stabilization and erosion control (Angers and Caron, 1998). Further, a recent economic analysis of composting found that using compost for transportation projects (such as site restoration) rather than purchasing topsoil or other medium can substantially increase the cost-effectiveness of a compost vessel (Moruza and Donaldson, 2015).

There were a few (3 to 5) small (less than 5 in) bones present in the compost that was spread on the test section (R. Smith, personal communication). Because the site is at a VDOT AHQ lot away from public view, the presence of the bones was not a concern to AHQ staff and the bones were not removed. Bone screening options have been studied by researchers at the

Virginia Cooperative Extension for their efficacy for screening cow mortality compost. Screening buckets attached to front loaders were found to be an efficient method of separating the bones (Clark et al., 2013). Renting the bucket is presently not an option in Virginia, and purchasing a bucket would cost approximately $25,000 (R. Clark, personal communication). Researchers at the Virginia Cooperative Extension are currently investigating means to purchase a bucket and rent it to state and local mortality composters. This may become an option for future VDOT compost end use projects that are in public view.

Figure 15. Comparison of 2 Plots at VDOT's Bethel AHQ Covered With Grass Seed, With and Without Application of a 2-in Layer of Compost (a Compost Blanket) Generated From the Forced Air System. The lower photos were taken 4 weeks after grass seed application.

SUMMARY OF FINDINGS

Analyses of Compost Generated From Forced Air System

- *For two of the three compost test sections, Solvita maturity test results and qualitative observations indicated that compost was mature, or finished, earlier than what was indicated by temperature. Using temperature as a primary indicator of finished compost was the most conservative method of determining compost maturity.*

- *Compost that was removed from the forced air containers as early as 6 weeks and transferred to curing areas met temperature thresholds indicative of mature compost more* *quickly than compost that remained in the container longer than 6 weeks.* The reason for this may be that there was a lesser potential for heat loss of compost in the containers or that the additional aeration achieved during the transfer of compost to a curing area sped the decomposition and maturation process.

- *For seeds grown with samples of the youngest compost (6 weeks old), there was a long delay of germination, indicative of immaturity*. Plants grown with 9- and 12-week-old compost had a germination index of 76% and 100%, respectively, and grew significantly larger (by weight) than those grown with soil.

- *With the use of temperature as the primary indicator of maturity and support by the other tests, compost was mature under the following two treatments: (1) 6 weeks in the container and a subsequent 8.5 weeks in a curing area, and (2) 9 weeks in the container and a subsequent 8.5 weeks in a curing area.* The temperature of compost that remained in the container for at least 12 weeks remained high, suggesting that cooling in a curing area is necessary for compost prior to application.

Analyses of Compost Generated From Rotary Drum

- *Solvita maturity tests and qualitative observations indicated that compost that emerged from the drum required further curing in a curing area before reaching maturity.*

- *Temperature could not be reliably measured within the drum because the material was being rotated. Transferring compost from the drum to curing areas was a reliable means to measure temperature accurately. Using temperature as a primary indicator of finished compost in the curing areas was the most conservative method of determining compost maturity.*

- *Seeds grown with compost that had newly emerged from the drum had a long delay of germination, indicative of compost immaturity. Plants grown with compost that cured in a curing area for 6 and 9 weeks had a germination index of 111% and 104%, respectively, and grew significantly larger than those grown with soil.*

- *With the use of temperature as the primary indicator of maturity and support by the other tests, compost that emerged from the drum was mature after being transferred to a curing area to cure for approximately 8 weeks.*

CONCLUSIONS

- *Compost generated from a forced air system can be transferred to curing areas as early as 6 weeks after mortalities are loaded into the vessel; the compost will be mature and suitable for application after remaining in the curing area for a minimum of 8.5 weeks.* After curing for this time period, verifying that the temperature is no greater than 30° F above ambient is expected to ensure that compost is finished before application for transportation projects.

- *Compost generated from the rotary drum requires a minimum of 8 weeks in a curing area to reach maturity.* Leaving compost in curing areas to cure for a minimum of 2 months and verifying that the temperature is no greater than 30° F above ambient is expected to ensure that compost is finished before application for transportation projects.

- *Mature compost generated from the forced air system and rotary drum meets the U.S. EPA compost specifications and is therefore suitable for transportation applications.*

RECOMMENDATIONS

1. *VCTIR and VDOT's Environmental Division, should incorporate the following findings from this study into a VDOT animal mortality composting guidance document:*

    - *VDOT maintenance personnel who manage a forced air compost vessel should remove the compost from the containers no sooner than 8 weeks to be used as a carbon source in another container or to store in a curing area to cure for a minimum of 8.5 weeks.*

    - *VDOT maintenance personnel who manage a rotary drum should transfer the compost that exits the drum to a curing area to cure for a minimum of 8 weeks.*

    - *To ensure that compost is finished after its transfer to a curing area, VDOT maintenance personnel should ensure that the temperature is no greater than 30° F above ambient prior to application of the compost for transportation projects.*

2. *VDOT maintenance personnel should consider using finished compost for applications such as controlling erosion; using berms for stormwater runoff control and sediment filtration; and amending soil to establish grass or other vegetation.*

3. *VDOT's Maintenance Division should evaluate the guidelines in the draft composting guidance document and if approved incorporate them into the VDOT Maintenance Best Practices Manual.*

IMPLEMENTATION PLAN

As detailed earlier in this report, VDOT's Environmental Division and VCTIR held meetings with DEQ to share the findings of the VCTIR composting research. These discussions resulted in an MOU (finalized in early 2015) between VDOT and DEQ to govern the conditions under which VDOT may perform composting of roadway animal mortality (DEQ and VDOT, 2015). The provisions in the MOU replace the more stringent state composting requirements, such as siting, construction, and compost testing requirements (Virginia Register of Regulations, 2011). This is expected to increase composting implementation prospects for VDOT.

Implementation of the recommendations in this report is underway. VCTIR has incorporated the findings from this study into a draft guidance document for VDOT animal mortality composting. The state maintenance division administrator has reviewed the draft and provided approval for its incorporation into the VDOT *Maintenance Best Practices Manual*. The draft composting guidance document is currently being finalized.

ACKNOWLEDGMENTS

This study was possible because of the assistance from VDOT AHQ staff who constructed experimental compost piles for the purpose of this study and provided temperature and mortality loading information. Appreciation is extended to Dustin Dickens and Robert Huffman at VDOT's Fishersville AHQ. Special thanks go to Tom Anderson, Roger Bennett, Derek Daniels, Randy Martin, Ross Poppe, and Roy Smith at VDOT's Bethel AHQ. The authors are also grateful to the contributions from and reviews by VDOT's Ed Wallingford and David Wilson and VCTIR's Mary Bennett, Linda Evans, Jose Gomez, Amy O'Leary, and Jimmy White.

REFERENCES

Alexander, R. Compost Use on Roadside Projects. In *Beneficial Use of Recycled Materials in Transportation Applications,* T. Eighmy, Ed. Air and Waste Management Association, Sewickley, PA, 2003, pp. 1015-1021.

American Association of State Highway Transportation Officials. Standard Practice for Compost for Erosion/Sediment Control (Compost Blanket). In *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 33rd ed. Washington, DC, 2013a.

American Association of State Highway Transportation Officials. Standard Practice for Compost for Erosion/Sediment Control (Filter Berms and Filter Socks). In *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 33rd ed. Washington, DC, 2013b.

Angers, D.A., and Caron, J. Plant-induced Changes in Soil Structure: Processes and Feedbacks. *Developments in Biogeochemistry*, Vol. 42, 1998, pp. 55-72.

Baca, M.T., Delgado, C., Sanchez-Raya, A.J., and Gallardo-Lara, F. Comparative Use of Cress Seed Germination and Physiological Parameters of Helianthus anuus L. to Assess Compost Maturation. *Biological Wastes*, Vol. 33, 1990, pp. 251-261.

Bonhotal, J., and Shwarz, M. Environmental Effects of Mortality Disposal. In *Proceedings of the 3rd International Symposium: Management of Animal Carcasses, Tissue & Related Byproducts.* Davis, CA, July 21-23, 2009, pp. 1-10.

Bonhotal, J., Harrison, E.Z., and Shwarz, M. *Composting Road Kill*. Cornell Waste Management Institute, Ithaca, NY, 2007. http://cwmi.css.cornell.edu/roadkillfs.pdf. Accessed May 27, 2014.

Brinton, W.F. *Compost Quality Standards and Guidelines: An International View*. Woods End Research Laboratory, Inc. 2000. http://solvita.com/pdf-files/nysar-ne.pdf. Accessed February 10, 2014.

Brinton, W.F., Bonhotal, J., and Fiesinger, T. Compost Sampling for Nutrient and Quality Parameters: Variability of Sampler, Timing, and Pile Depth. *Compost Science & Utilization,* Vol. 20, No. 3, 2012, pp. 141-149.

Canadian Council of Ministers of the Environment. *Guidelines for Compost Quality*. Winnipeg, Manitoba, Canada, 2005. http://www.ccme.ca/assets/pdf/compostgdlns_1340_e.pdf. Accessed December 2, 2013.

Chanyasak, V., and Kubota, H. Carbon/Organic Nitrogen Ratio in Water Extracts As Measure of Composting Degradation. *Journal of Fermentation Technology*, Vol. 59, No. 3, 1981, pp. 215-219.

Chen, L., de Haro Marti, M., Moore, A., and Falen, C. *Dairy Compost Production and Use in Idaho: The Composting Process*. University of Idaho, Moscow, 2011. http://www.extension.uidaho.edu/nutrient/culturalpractices/PDF/The%20composting%20Process.pdf. Accessed December 8, 2014.

Clark, R.A., Peer, R., and Evanylo, G. *Field Test Screening and Beneficial Reuse of Large Animal Mortality Compost.* Virginia Cooperative Extension, Blacksburg, 2013. http://offices.ext.vt.edu/shenandoah/programs/anr/AgricultureandNaturalResources/Screening_Beneficial_Re-Use_Report-March_2013.pdf. Accessed June 16, 2014.

Composting Council Research and Education Foundation and the United States Composting Council. *Compost Use on State Highway Applications.* Harrisburg, PA, 2008. http://www.epa.gov/wastes/conserve/composting/highway/. Accessed February 13, 2014.

Deno, N.C. *Seed Germination Theory and Practice, 2nd Generation.* U.S. Department of Agriculture, Beltsville, MD, 1993. http://naldc.nal.usda.gov/download/41278/PDF. Accessed November 12, 2013.

Donaldson, B.M. *Evaluation of a Rotary Drum to Compost Animal Mortality*. Technical Assistance Report. Virginia Center for Transportation Innovation and Research, Charlottesville, 2014.

Donaldson, B.M., and Moruza, A.K. *An Assessment of the Animal Carcass Disposal Practices of the Virginia Department of Transportation and Guidance for the Selection of*

Alternative Carcass Management Options. VTRC 10-R7. Virginia Transportation Research Council, Charlottesville, 2010.

Donaldson, B.M. and White, J.W., Jr. *Composting Animal Mortality Removed From Roads: A Pilot Study of Rotary Drum and Forced Aeration Compost Vessels.* VCTIR 13-R8. Virginia Center for Transportation Innovation and Research, Charlottesville, 2013.

Donaldson, B.M., Smith, G.P., Kweon, Y.J., Sriranganathan, N., and Wilson, D.L. *Composting Animal Carcasses Removed From Roads: An Analysis of Pathogen Destruction and Leachate Constituents in Deer Mortality Static Windrow Composting*. VCTIR 12-R12. Virginia Center for Transportation Innovation and Research, Charlottesville, 2012.

Gallardo-Lara, F., and Nogales, R. Effect of the Application of Town Refuse Compost on the Soil-Plant System: A Review. *Biological Wastes*, Vol. 19, 1987, pp. 35-62.

Glanville, T.D., Richard, T.L., and Persyn, R.A. *Impacts of Compost Blankets on Erosion Control, Revegetation, and Water Quality at Highway Construction Sites in Iowa*. Iowa State University of Science and Technology, Agricultural and Biosystems Engineering Department, Ames, 2003.

Goldstein, N. Overview of Transportation Projects Utilizing Compost. In *Beneficial Use of Recycled Materials in Transportation Applications,* T. Eighmy, Ed. Air and Waste Management Association, Arlington, VA, 2003, pp. 1009-1014.

Haug, R.T. *The Practical Handbook of Compost Engineering*. Lewis Publishers, Boca Raton, FL, 1993.

Itavaara, M., Vikman, M., Liisa, M., and Vuorinen, A. Maturity Tests for Composts: Verification of a Test Scheme for Assessing Maturity. *Compost Science & Utilization,* Vol. 18, No. 3, 2010, pp. 174-183.

Miyatake, F., and Iwabuchi, K. Effect of High Compost Temperature on Enzymatic Activity and Species Diversity of Culturable Bacteria on Cattle Manure Compost. *Bioresource Technology,* Vol. 96, No. 16, 2005, pp. 1821-1825.

Moruza, A.K., and Donaldson, B.M. *An Evaluation of the Economics and Logistics of Animal Mortality Composting for the Virginia Department of Transportation.* VCTIR 15-R18. Virginia Center for Transportation Innovation and Research, Charlottesville, 2015.

Rajamäki, T., Arnold, M., Venelampi, O., Vikman, M., Räsänen, J., and Itävaara, M. Electronic Nose and Indicator Volatiles in Composting Process Monitoring. *Water, Air, and Soil Pollution,* Vol. 162, 2005, pp. 71-87.

Reinhardt, T. Organic Acids As a Decisive Limitation to Process Dynamics During Composting of Organic Matter. In *Microbiology of Composting,* H. Insam, N. Riddech, and S. Klammer, Eds. Springer Publishers, Verlag, Berlin, Heidelberg, Germany, 2002.

Rynk, R., van de Kamp, M., Wilson, G.B., Singley, M.E., Richard, T.L., Kolega, J.J., Gouin, F.R., Laliberty, L., Jr., Kay, D., Murphy, D.W., Hoitink, H.A.J., and Brinton, W.F. *On-Farm Composting Handbook.* Natural Resource, Agriculture, and Engineering Service, Ithaca, NY,1992.

Steger, K., Sjogren, A.M., Jarvis, A., Jansson, J.K., and Sundh, I. Development of Compost Maturity and Actinobacteria Populations During Full-Scale Composting of Organic Household Waste. *Journal of Applied Microbiology*. Vol. 3, No. 2, 2007, pp. 487-498.

University of Florida: Florida's Online Composting Center. Compost Maturity Tests. 2011. http://sarasota.ifas.ufl.edu/compost-info/tutorial/compost-maturity-test.shtml. Accessed September 23, 2013.

U.S. Composting Council. Seal of Testing Assurance. 2010. http://compostingcouncil.org/. Accessed December 30, 2013.

U.S. Composting Council. Sample Collection and Laboratory Preparation. Field Sampling of Composting Materials 02.01. 2001. http://compostingcouncil.org/admin/wp-content/plugins/wp-pdfupload/pdf/34/TMECC%20Field%20Sampling%20Protocol.pdf. Accessed October 5, 2014.

U.S. Environmental Protection Agency. *Environmental Regulations and Technology: Control of Pathogens and Vector Attraction in Sewage Sludge*. EPA/625/R-92/013. Cincinnati, OH, 2003.

U.S. Environmental Protection Agency. *Composting—Environmental Benefits*. 2014. http://www.epa.gov/compost/benefits.htm. Accessed June 2, 2014.

Virginia Department of Environmental Quality and Virginia Department of Transportation. Memorandum of Understanding Between the Virginia Department of Environmental Quality and the Virginia Department of Transportation: Composting Animal Road Mortality From VDOT Maintenance Roadway Operations. Virginia Department of Environmental Quality, Richmond, 2015.

Virginia Register of Regulations. *Virginia Solid Waste Management Regulations*, *9 VAC 20-81*. 2011. http://lis.virginia.gov/cgi-bin/legp604.exe?000+reg+9VAC20-81. Accessed February 5, 2014.

Warman, P.R. Evaluation of Seed Germination and Growth Tests for Assessing Compost Maturity. *Compost Science & Utilization,* Vol. 7, No. 3, 1999, pp. 33-37.

Woods End Laboratories, Inc. Laboratory Test Interpretation. *Journal of Woods End Laboratories, Inc*., *Version 10*. Mt. Vernon, ME, 2013.